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# SSC-305

# INVESTIGATION OF STEELS FOR IMPROVED WELDABILITY IN SHIP CONSTRUCTION PHASE II

SSC-305 INVESTIGATION OF STEELS FOR IMPROVED WELDABILITY IN SHIP CONSTRUCTION PHASE II 1981





SHIP STRUCTURE COMMITTEE

1981

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**Ship Structure Committee**

An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

Address Correspondence to:

Secretary, Ship Structure Con ittee
U.S. Coast Guard Headquarters, (G-M/TP 13)
Washington, D.C. 20593

SR-1256

1981

Much of the modernization taking place in the world shipbuilding industry in the last decade has centered around the use of new, more efficient welding techniques. The potential increase in productivity with new high-deposition rate welding processes is considerable. However, in order to take full advantage of the benefits of the new welding practices, additional metallurgical control appears necessary for minimizing heat-affected zone and weld-metal property degradation.

The Ship Structure Committee is now sponsoring a project directed toward determining the weld procedure and metallurgical control necessary to develop adequate toughness in the weldment, using high-deposition rate welding procedures. This report describes the second phase of that work.

Clyde T. Lusk, Jr.
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

**Technical Report Documentation Page**

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15. Supplementary Notes

The U.S.Coast Guard performs the contracting services for the Ship Structure Committee.

16. Abstract


The purpose of the present three-phase investigation is to develop economical ship-plate steels with improved heat-affected-zone (HAZ) toughness when welded at high heat inputs. The first phase consisted of a literature review aimed at identifying economical compositions and processing methods that were expected to result in steels having good HAZ toughness when welded at high heat inputs. This review resulted in the selection of 20 steels to be melted and evaluated at the Research Laboratory.

The present report summarizes Phase II. During this phase, the 20 laboratory-melted steels were produced with compositional variations in the content of titanium, nitrogen, vanadium, boron, calcium, and rare-earth metals. These steels were rolled to 1-inch-thick plate and normalized. Thermal cycles occurring in the HAZ near the fusion line of high-heat-input welds were simulated in samples of all these steels. On the basis of the toughness and microstructure of these simulated-weld samples, eight of the laboratory-melted steels were selected for welding along with three commercially produced ship steels. In addition to submerged-arc (SA) welding at a typical heat input of 75 kJ/inch, two high-heat-input welding processes were used: (1) electroslag welding (ES) at about 1000 kJ/inch and (2) two-pass SA welding at 180 kJ/inch per pass.

Charpy V-notch tests of the HAZ of these steels showed that the steel with the best HAZ toughness for the ES weld was a calcium-treated 0.08 percent vanadium steel with a low content of residual elements (Ni, Cu, Cr, and Mo). Several titanium steels without boron and also one with boron had good HAZ toughness when ES-welded. The HAZ toughness of the 0.08 percent vanadium steel and several of the titanium steels was also good when the steels were SA-welded at 180 kJ/inch. However, two of the three titanium steels that contained boron had poor HAZ toughness for a normal-heat-input (75 kJ/inch) SA weld. Overall, vanadium, low-residual-element steels, and titanium steels without boron appear to show promise of providing improved HAZ toughness in high-heat-input welds.


| 17. Key Words | | 18. Distribution Statement |
|---|---|---|
| Weld | Rare-Earth Metals | This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161 |
| Heat Affected Zone | Submerged Arc Weld | |
| Steel | Electroslag Weld | |
| Toughness | Charpy V-notch | |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
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# METRIC CONVERSION FACTORS

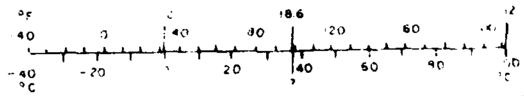
## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.


## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



CONTENTS

## Introduction

The purpose of the present project is to develop economical ship-plate steels having improved heat-affected-zone (HAZ) toughness when welded with high-heat inputs. Phase I of this project consisted of a literature search for steels that were reported to have improved HAZ toughness when welded with high-heat inputs or when heat-treated to simulate the thermal cycle in a weld HAZ. The literature search also identified steels that had high grain-coarsening temperatures and that should, therefore, have a narrow coarse-grain weld HAZ. On the basis of this literature search, 20 steel compositions were selected for melting and evaluation at the Research Laboratory. The results of the literature search, the reasons for the selection of the various steel compositions, and details of the testing program were presented in the report[1)] on Phase I of this project.

During Phase II, the 20 laboratory-melted steels were produced, and three commercially produced ship-plate steels were obtained for comparison. The thermal cycles occurring in the HAZ adjacent to the bond line were reproduced in samples of all the investigated steels by using a Gleeble machine. On the basis of the toughness results and microstructures of these Gleeble-treated samples, eight steels in addition to the commercially produced plates were selected for welding with typical and high-heat inputs. The effects of the various alloying additions on the HAZ toughness and microstructure were determined. Details of Phase II are contained in the present report.

## Materials and Experimental Work

### Commercially Produced Plates

Three one-inch-thick (25 mm) plates of commercially produced ship steels were included in the present program as reference materials. One plate was a calcium-treated ABS V-051 steel produced by Lukens Steel Company. The second plate was Nippon Steel Corporation's HT-50S Class D plate developed for one-pass (high heat input) submerged-arc welding. The third plate was ABS CS steel produced by U. S. Steel Corporation (USSC). All of the plates were received in the normalized condition.

### Laboratory-Melted Steels

Table I shows the aim chemical composition and plate check analyses of 20 laboratory-melted steels. These 500-pound (227 kg)

# Table I Chemical Composition of the Steels Investigated--Percent

| No. | Steel Description | | C | Mn | P | S | Si | Cu | Ni | Cr | Mo | Cb | V | Ti | Al | Ca | B | N | Ce |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | |
| | **Reference Laboratory-Melted Steels** | | | | | | | | | | | | | | | | | | |
| 1 | Reference ABS V-051 | Aim | 0.13 | 1.38 | 0.010 | 0.006 | 0.16 | - | - | - | - | 0.027 | - | - | 0.030 | * | - | 0.004 | - |
| | | Check | 0.12 | 1.38 | 0.008 | 0.006 | 0.14 | 0.004 | 0.004 | <0.003 | 0.006 | 0.023 | <0.002 | <0.002 | 0.027 | <0.0003 | 0.0004 | 0.007 | NA1) |
| 2 | Reference ABS DS | Aim | 0.14 | 1.25 | 0.010 | 0.020 | 0.22 | - | - | - | - | - | - | - | 0.030 | - | - | 0.004 | - |
| | | Check | 0.13 | 1.29 | 0.011 | 0.022 | 0.22 | 0.003 | 0.002 | <0.003 | 0.007 | <0.005 | <0.002 | <0.002 | 0.030 | NA | 0.0003 | 0.005 | NA |
| | **Base Steel and Effects of S, Ca, Cb, V, REM, Residuals** | | | | | | | | | | | | | | | | | | |
| 3 | Base+S | Aim | 0.12 | 1.35 | 0.010 | 0.020 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | - | 0.030 | - | - | 0.008 | - |
| | | Check | 0.11 | 1.40 | 0.009 | 0.023 | 0.28 | 0.18 | 0.14 | 0.13 | 0.04 | - | <0.002 | <0.002 | 0.030 | NA | 0.0001 | 0.008 | NA |
| 4 | Base | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | - | 0.030 | - | - | 0.008 | - |
| | | Check | 0.11 | 1.35 | 0.009 | 0.007 | 0.29 | 0.18 | 0.15 | 0.14 | 0.04 | - | <0.002 | 0.003 | 0.025 | NA | 0.0002 | 0.010 | NA |
| 5 | Base+Ca | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | - | 0.030 | * | - | 0.008 | - |
| | | Check | 0.12 | 1.38 | 0.009 | 0.006 | 0.29 | 0.19 | 0.15 | 0.14 | 0.04 | <0.005 | <0.002 | <0.002 | 0.030 | <0.0003 | 0.0004 | 0.010 | NA |
| 6 | Base+Cb-R2) | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | - | - | - | - | 0.025 | - | - | 0.030 | * | - | 0.008 | - |
| | | Check | 0.11 | 1.37 | 0.008 | 0.006 | 0.28 | 0.004 | 0.004 | <0.003 | 0.008 | 0.023 | <0.002 | <0.002 | 0.032 | <0.0003 | 0.0003 | 0.009 | NA |
| 7 | Base+Ca+V-R2) | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | - | - | - | - | - | 0.080 | - | 0.030 | * | - | 0.008 | - |
| | | Check | 0.12 | 1.33 | 0.008 | 0.007 | 0.24 | 0.004 | 0.003 | <0.003 | 0.008 | <0.005 | 0.077 | <0.002 | 0.027 | <0.0003 | 0.0002 | 0.010 | NA |
| 8 | Base+Cb+REM-R2) | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | - | - | - | - | 0.025 | - | - | 0.030 | - | - | 0.008 | 0.015 |
| | | Check | 0.12 | 1.38 | 0.008 | 0.008 | 0.27 | 0.004 | <0.002 | <0.003 | 0.008 | 0.023 | <0.002 | <0.002 | 0.031 | NA | 0.0003 | 0.011 | 0.013 |
| | **B-Ti-REM-N Combinations** | | | | | | | | | | | | | | | | | | |
| 9 | Base+REM+B | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | - | 0.030 | - | 0.003 | 0.005 | 0.015 |
| | | Check | 0.11 | 1.37 | 0.008 | 0.008 | 0.27 | 0.18 | 0.14 | 0.14 | 0.04 | <0.005 | <0.002 | <0.002 | 0.028 | NA | 0.0029 | [illegible] | 0.016 |
| 10 | Base+REM+B+N | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | - | 0.030 | - | 0.003 | 0.010 | 0.015 |
| | | Check | 0.12 | 1.37 | 0.008 | 0.005 | 0.29 | 0.20 | 0.15 | 0.14 | 0.04 | <0.005 | <0.002 | 0.003 | 0.032 | NA | 0.0034 | 0.010 | 0.015 |
| 11 | Base+REM+B+Ti | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.015 | 0.030 | - | 0.003 | 0.010 | 015 |
| | | Check | 0.11 | 1.38 | 0.008 | 0.005 | 0.28 | 0.20 | 0.16 | 0.14 | 0.04 | <0.005 | <0.002 | 0.016 | 0.031 | NA | 0.0035 | 0.007 | [illegible] |

(Continued)

Table I (Continued)

| No. | Steel Description | | C | Mn | P | S | Si | Cu | Ni | Cr | Mo | Cb | V | Ti | Al | Ca | B | N | Ce |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Ti-N-B-Al Combinations** | | | | | | | | | | | | | | | | | | |
| 12 | Base+Ti+lowAl, | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.013 | 0.010 | - | - | 0.005 | - |
| | heated once | Check | 0.12 | 1.36 | 0.012 | 0.007 | 0.31 | 0.18 | 0.14 | 0.14 | 0.04 | <0.005 | <0.002 | 0.017 | 0.012 | NA | 0.0001 | 0.006 | NA |
| 13 | Base+Ti, | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.013 | 0.030 | - | - | 0.005 | - |
| | heated once | Check | 0.12 | 1.37 | 0.010 | 0.008 | 0.32 | 0.18 | 0.14 | 0.15 | 0.04 | <0.005 | <0.002 | 0.017 | 0.030 | NA | 0.0001 | 0.006 | NA |
| 14 | Base+Ti+N, | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.025 | 0.030 | - | - | 0.010 | - |
| | heated once | Check | 0.11 | 1.42 | 0.011 | 0.008 | 0.33 | 0.20 | 0.14 | 0.13 | 0.04 | <0.005 | <0.002 | 0.030 | 0.032 | NA | 0.0001 | 0.011 | NA |
| 15 | Base+Ti+N+B, | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.025 | 0.030 | - | 0.003 | 0.010 | - |
| | heated once | Check | 0.11 | 1.37 | 0.008 | 0.007 | 0.28 | 0.18 | 0.14 | 0.14 | 0.04 | - | <0.002 | 0.032 | 0.024 | NA | 0.0033 | 0.013 | NA |
| | **Ti-N-Ca-REM Combinations** | | | | | | | | | | | | | | | | | | |
| 16 | Base+Ti+Ca | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.020 | 0.030 | * | - | 0.008 | - |
| | | Check | 0.12 | 1.40 | 0.009 | 0.006 | 0.28 | 0.18 | 0.14 | 0.14 | 0.04 | <0.005 | <0.002 | 0.025 | 0.032 | <0.0003 | 0.0004 | 0.009 | NA |
| 17 | Base+Ti+Ca | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.015 | 0.030 | * | - | 0.006 | - |
| | | Check | 0.12 | 1.35 | 0.009 | 0.006 | 0.28 | 0.18 | 0.15 | 0.14 | 0.04 | <0.005 | <0.002 | 0.014 | 0.029 | <0.0003 | 0.0004 | 0.009 | NA |
| 18 | Base+Ti+REM+ | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.015 | 0.030 | * | - | 0.006 | 0.015 |
| | Ca | Check | 0.11 | 1.37 | 0.011 | 0.006 | 0.28 | 0.18 | 0.15 | 0.14 | 0.04 | <0.005 | <0.002 | 0.015 | 0.032 | <0.0003 | 0.0003 | 0.007 | 0.015 |
| 19 | Base+Ti+B+ | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.30 | 0.20 | 0.15 | 0.15 | 0.04 | - | - | 0.015 | 0.030 | * | 0.003 | 0.006 | - |
| | Ca | Check | 0.12 | 1.35 | 0.009 | 0.006 | 0.28 | 0.18 | 0.14 | 0.14 | 0.04 | - | <0.002 | 0.014 | 0.028 | <0.0003 | 0.0030 | 0.009 | NA |
| | **V-B** | | | | | | | | | | | | | | | | | | |
| 20 | Base+B-R-Si | Aim | 0.12 | 1.35 | 0.010 | 0.006 | 0.04 | - | - | - | - | - | 0.06 | - | 0.030 | - | 0.003 | 0.007 | - |
| | +V | Check | 0.12 | 1.34 | 0.012 | 0.006 | 0.05 | 0.004 | 0.003 | <0.003 | <0.003 | <0.005 | 0.056 | 0.002 | 0.029 | NA | 0.0032 | 0.008 | NA |
| | **Commercially Produced Steels** | | | | | | | | | | | | | | | | | | |
| N3) | HT-50S | Check | 0.11 | 1.59 | 0.012 | 0.004 | 0.30 | 0.01 | 0.02 | <0.003 | 0.007 | <0.005 | <0.002 | 0.021 | 0.019 | - | 0.0001 | 0.008 | <0.01 |
| L4) | ABS V-051 | Check | 0.13 | 1.44 | 0.009 | 0.005 | 0.15 | 0.19 | 0.09 | 0.09 | 0.03 | 0.028 | <0.002 | - | 0.050 | 0.0027 | 0.0001 | 0.011 | <0.01 |
| U5) | ABS-CS | Check | 0.12 | 0.99 | 0.007 | 0.017 | 0.19 | 0.11 | 0.08 | 0.06 | 0.02 | <0.005 | <0.002 | <0.002 | 0.015 | - | - | 0.007 | - |

1) NA means none added and not analyzed.
2) R means without added residuals (Cu, Ni, Cr, and Mo).
3) Nippon HT-50S (D grade), heat No. TE4327.
4) Lukens V051 Frostline, heat No. B1430.
5) U. S. Steel, ABS-CS, heat No. 4G2382.

* Ca was added as a 20% Ca, 80% Fe proprietary additive. Canisters containing this additive were plunged into the ladle three times with a total amount of Ca which would amount to 0.027% in the steel if none were lost.

heats were induction melted in a vacuum furnace and poured into 7- by 12- by 24-inch (178 by 305 by 610 mm) ingot molds. All the ingots were cooled to room temperature. Sixteen of the 20 ingots were reheated to 2350°F (1290°C) and rolled in the 24-inch direction to 5-inch-thick (127 mm) slabs, which were air-cooled to room temperature. These slabs were reheated to 2350°F and rolled longitudinally to 1-inch-thick plate in 12 passes of about 13 percent reduction per pass with a final-pass temperature of 1900°F (1040°C) as measured by an optical pyrometer.

As discussed in the report[1] on Phase I of this project, the literature indicates that to produce the fine titanium nitride particles that restrict grain coarsening, the cooling rate of the ingot down to 2010°F (1100°C) must be fast enough (≥9°F or 5°C per minute) to prevent the formation of coarse titanium nitride particles. Furthermore, some investigators state that the steel must not be reheated more than once above about 2000°F (1095°C). Cooling rates for slabs from continuous casters exceed this specified cooling rate and so do those for the small laboratory-melted steels in the present investigation. Continuous-cast slabs are generally heated only once for rolling to plate, so the titanium nitrides should not coarsen; whereas ingots, or at least the outer and cooler portions of ingots, are generally reheated twice above 2000°F—once for rolling to slab and once for rolling to plate.

In the present investigation, four steels containing titanium, Steels 12, 13, 14, and 15, were processed in a manner that simulates the commercial production of plate from continuous-cast slabs. That is, these four ingots were reheated only once and rolled directly to plate. The heating temperature was 2350°F, and the ingots were rolled straightaway to 1-inch-thick plate in 15 passes of about 12 percent reduction each, with a final pass temperature of 1900°F. Several other titanium-containing steels shown in Table I (Steels 11 and 16 through 19) were among the 16 steels reheated twice for rolling, but according to the literature, other elements present in addition to the titanium (calcium and/or rare earth metals) permit such processing.[2,3]

Eight laboratory-melted steels were calcium treated. In production, calcium is often injected as a calcium silicide powder with an inert-gas carrier. The usual purpose of the calcium addition is to reduce the sulfur content of the molten steel and to form sulfides that are hard and do not string out at the plate-rolling temperature. Additionally, calcium was added to some of the laboratory-melted steels containing titanium—steels 16 through 19—because it is claimed[2,3] that fine calcium-containing precipitates form and act as nuclei for the precipitation of titanium nitride, which retards grain coarsening.

As equipment to inject a calcium powder was not available at the Laboratory, cannisters containing a 20 percent calcium and 80 percent iron proprietary additive were secured to the end of a rod and plunged into the ladle. Because the reaction of calcium with the molten steel is highly exothermic, the calcium addition was made in three separate plunges to prevent the reaction from expelling the additive from the ladle. The total amount of calcium added would have amounted to 0.027 percent in the steel if none were lost.

Plate rolled from the first trial showed that the calcium addition was only partially effective in balling sulfides—some were strung out, some were short, and some were balled. Therefore, two more trials were made, one with the calcium silicide often used for production of commercial heats, and one with twice as much of the aforementioned calcium-iron additive. Sulfides in the plate from these two trials were also only partially balled and the inclusion content of these steels was undesirably greater. Therefore, the first of the above-described practices was used in making the eight calcium-treated steels.

The plates from the laboratory-melted steels were normalized by treating them in a 1675°F (913°C) furnace for one hour and air cooling them.

## Mechanical Testing of Unwelded Plates

Eighteen transverse Charpy V-notch (CVN) specimens and duplicate 0.357-inch-diameter (9.07 mm) tension-test specimens were machined from the quarterthickness of each of the plates. The CVN specimens were tested over a range of temperatures to establish transition behavior and the tension-test specimens were tested at room temperature.

## Gleeble Treatment

Before the Gleeble could be used to simulate the thermal cycles that occur in the HAZ near the fusion zone, it was necessary to determine the time-temperature cycles for the high-heat-input welding conditions that would be used in this study. Therefore, time-temperature measurements were made in an ES and in an SA weldment with embedded thermocouples. Because the ABS-specified location for Charpy V-notch testing is the plate quarterthickness on the last-pass side of a weldment, the thermocouples were placed at this position. As the location of the bond line could not be precisely predicted, seven thermocouples were used; one was placed

at the expected location of the bond line, and three were placed on each side of the center thermocouple at 0.030-inch (0.75 mm) increments from the expected bond-line location.

The highest temperatures recorded for surviving thermocouples in the weldments were 2525°F (1385°C) for the ES weld and 2545°F (1396°C) for the SA weld. The data from this experiment are shown in Table II and were used in the Gleeble simulations, except that a peak temperature of 2525°F was used for both weld simulations so that differences caused by the two treatments would reflect differences in heating and cooling rather than differences in an arbitrarily chosen peak temperature. The location of this peak temperature in the HAZ is only a fraction of a millimeter from the bond line. A peak temperature of 2525°F was chosen rather than 2462°F (1350°C), as often reported in the literature for HAZ simulations, because for the high-heat-input welding conditions used in this study, the location in the HAZ that had a peak temperature of 2462°F was outside the very-coarse-grain region for the steel used in these trials.

Twenty transverse oversize CVN specimen blanks were machined from each of the 23 plates. Ten blanks from each plate were treated with the Gleeble by using one of the thermal cycles shown in Table II, and the other 10 blanks from each plate were treated in accord with the other thermal cycle except that a peak temperature of 2525°F was used in both instances. The CVN specimens machined from these blanks were tested over a range of temperatures to determine transition behavior.

### Microstructure of Base Plate and Gleeble Samples

Samples of the plates were examined with a light microscope. The microstructure of all the plates consisted of ferrite and pearlite. Ferrite grain size and pearlite content were determined with a Quantitative Television Microscope.[4] In addition, light micrographs of the Gleeble-treated specimens from each steel were prepared to show the prior austenite grain size and resulting microstructure.

### Welding Procedures

In addition to the three commercially produced plates and the base steel from the laboratory heats, seven of the more promising steels were welded and evaluated. These seven steels were selected on the basis of the CVN test results from the Gleeble-treated samples, the microstructure of these samples, and a consideration of the alloy system to which the steels belonged.

Table II Temperature Measurements in Weld Heat-Affected Zones

| Electroslag Weld | | 180 kJ/in. Submerged-Arc Weld | |
|---|---|---|---|
| Time, sec | Temperature, °F | Time, sec | Temperature, °F |
| 0 | 75 | 0 | 192 |
| 600 | 500 | 4 | 232 |
| 660 | 1000 | 9 | 2545 |
| 690 | 2100 | 13 | 2505 |
| 700 | 2525 | 17 | 2381 |
| 708 | 2522 | 22 | 2232 |
| 712 | 2484 | 26 | 2090 |
| 717 | 2443 | 31 | 1965 |
| 721 | 2402 | 35 | 1843 |
| 725 | 2322 | 39 | 1730 |
| 729 | 2278 | 43 | 1632 |
| 734 | 2227 | 48 | 1550 |
| 742 | 2148 | 52 | 1483 |
| 759 | 2042 | 56 | 1428 |
| 768 | 2003 | 60 | 1380 |
| 776 | 1922 | 69 | 1301 |
| 785 | 1843 | 77 | 1241 |
| 802 | 1716 | 86 | 1195 |
| 819 | 1602 | 94 | 1160 |
| 836 | 1502 | 103 | 1133 |
| 853 | 1414 | 112 | 1104 |
| 874 | 1320 | 125 | 1052 |
| 899 | 1231 | 134 | 1019 |
| 933 | 1133 | 146 | 973 |
| 971 | 1046 | 168 | 915 |
| 1024 | 950 | 180 | 884 |
| 1066 | 869 | 205 | 831 |
| 1125 | 773 | 222 | 801 |
| 1185 | 695 | 266 | 738 |
| 1245 | 627 | 387 | 624 |
| 1305 | 574 | 498 | 552 |
| 1365 | 527 | 618 | 498 |
| 1425 | 490 | 679 | 475 |

All welds were made in a longitudinal direction. Plate samples of each of the 11 steels were ES-welded at a heat input of about 1000 kJ/inch (40 kJ/mm) and SA-welded in two passes at a heat input of 180 kJ/inch (7.1 kJ/mm) per pass and in six passes at a more typical heat input of 75 kJ/inch (3.0 kJ/mm). The joint configurations and weld parameters are shown in Figure 1 and typical chemical compositions of the electrodes are given in Table III.

## CVN Testing of Weldments

For the commercially produced plates, CVN specimens were machined from the weldments in accordance with ABS and USCG qualification requirements. The CVN specimens were machined from the plate quarterthickness perpendicular to the weld direction with the notch normal to the plate surface and located at the center of the weld, at the bond line, and in the HAZ at distances of 1, 3, and 5 mm from the bond line, Figure 2. Because the bond line was rarely perfectly perpendicular to the plate surface over the entire thickness of the CVN specimen, different portions of the notch were generally at different distances from the bond line. Twelve CVN specimens were machined from each of the five test locations and tested in triplicate over a range of temperatures to determine transition behavior.

For the laboratory-melted steels, tests were conducted only on CVN specimens machined with the notch at the bond line and the 1- and 3-mm positions within the HAZ, but quintuplicate tests were conducted at 0 and -40°F (-18 and -40°C) for each of these three locations.

## Hardness Traverses of Weldments

Diamond pyramid hardness measurements were made at the plate quarterthickness in the center of the weld, in the base plate, and in the HAZ at distances of 1 and 3 mm from the bond line.

## Weld-HAZ Microstructure

Light micrographs of the HAZ from each of the 11 steels selected for welding were prepared showing the microstructure at the plate quarterthickness at magnifications of 50X, 200X, and 1000X.

Table III Typical Electrode Composion--Percent

| Electrode | Welding Process | C | Mn | Si | Cr | Ni | Mo | Cu |
|---|---|---|---|---|---|---|---|---|
| Armco W18 | Submerged-arc | 0.15 | 0.67 | 0.17 | 0.06 | 1.80 | 0.16 | 0.25 |
| Linde M1-88 | Electroslag | 0.06 | 1.65 | 0.35 | 0.25 | 1.50 | 0.40 | - |

Note: Above is filler metal manufacturer's data.

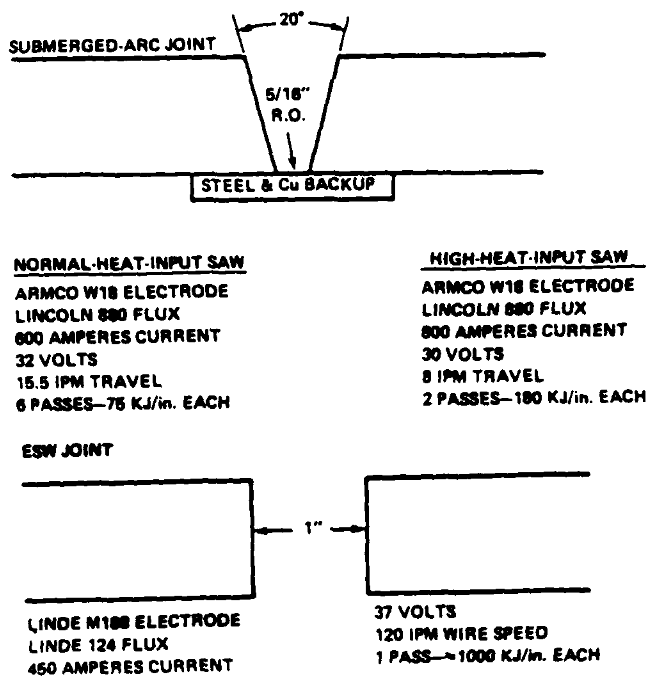



Figure 1. Joint configuration and Weld parameters used in current investigation

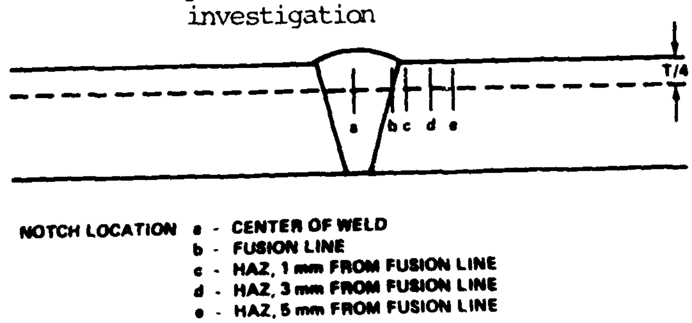



Figure 2. Schematic of Notch Location for CVN impact specimens

## Results and Discussion

### Base Plate

The tensile properties and CVN transition temperatures of the plates investigated are shown in Table IV, and individual CVN test results are given in Appendix Table A. Steel 4 is the base steel in the present study, and its chemical composition was chosen to provide a yield strength of about 50 ksi (345 MPa). The CVN 15 ft-lb (20J) transition temperature ($V_{15}$) of Steel 4 was -150°F (-100°C) and its 50 percent shear-fracture-appearance transition temperature ($V_{50}$) was -15°F (-25°C).

As will be shown subsequently, the only laboratory-melted steels in this investigation that showed significant improvements in HAZ toughness were those that contained titanium (Steels 11 through 19) and one steel that contained vanadium (Steel 7). Table IV shows that, as a group, these titanium steels had base-metal toughness considerably inferior to that of the titanium-free steels. The base-metal toughness of the vanadium steel, Steel 7, however, was about the same as that of the reference steel.

The microstructure of all the plates consisted of ferrite and pearlite. As Table V shows, the ferrite grain size of all the steels was fine, ranging from about ASTM No. 8 to 10. Because of the low-carbon content of the steels, the pearlite content was also low, ranging from 12 to 23 percent.

### Gleeble-Treated Steels

Individual CVN test results from the Gleeble-treated specimens are shown in Appendix Table B for the ESW simulation and in Appendix Table C for the 180 kJ/inch SAW simulation. Table VI shows the average CVN energy absorbed at 0°F (-18°C) and -40°F (-40°C) for each of the steels.

Table VI also shows the Rockwell B hardness of the Gleeble-treated samples. No significant correlation between hardness and toughness of these samples is apparent.

Light micrographs of all the Gleeble-treated steels were prepared at a magnification of 50X to show the prior austenite grain size and at 200X to show finer details of the microstructure. Prior austenite grain-size ratings for these samples are given in Table VI. In many instances, particularly for the coarser grain samples, the prior austenite grain boundaries were outlined by a continuous network of ferrite so that the grain size was well defined. For some samples, the prior austenite grain boundary was less distinct and, in a few instances, unratable.

Table IV Transverse Mechanical Properties of the Plates Investigated

| Steel | Tensile Properties* Yield Strength, ksi | Tensile Strength, ksi | Elongation in 1.4 In., % | Reduction of Area, % | Charpy V-Notch Transition Temperature, °F 15 ft-lb | 50% Shear |
|---|---|---|---|---|---|---|
| 1 | 50.1 | 67.8 | 34.5 | 72.4 | -125 | -40 |
| 2 | 44.4 | 65.6 | 34.0 | 65.9 | -80 | -10 |
| 3 | 49.9 | 70.8 | 32.5 | 67.9 | -140 | -20 |
| 4 | 50.0 | 70.3 | 35.0 | 74.0 | -150 | -15 |
| 5 | 52.2 | 73.8 | 33.0 | 73.2 | -190 | 0 |
| 6 | 51.5 | 70.9 | 34.5 | 73.6 | -155 | -35 |
| 7 | 52.6 | 71.7 | 34.0 | 73.2 | -130 | -10 |
| 8 | 51.3 | 71.0 | 35.3 | 77.5 | -145 | -75 |
| 9 | 47.1 | 70.7 | 34.3 | 74.8 | -175 | -35 |
| 10 | 47.3 | 71.1 | 34.0 | 73.1 | -155 | -5 |
| 11 | 44.8 | 70.0 | 35.0 | 77.0 | -45 | 20 |
| 12 | 48.2 | 70.1 | 34.0 | 71.7 | -90 | 30 |
| 13 | 47.5 | 70.3 | 33.5 | 70.2 | -80 | 30 |
| 14 | 48.3 | 71.0 | 33.5 | 71.2 | -95 | 20 |
| 15 | 46.8 | 69.3 | 34.0 | 71.0 | -60 | 60 |
| 16 | 47.3 | 70.8 | 34.5 | 73.5 | -60 | 30 |
| 17 | 49.5 | 71.5 | 34.0 | 72.9 | -105 | 40 |
| 18 | 46.5 | 70.8 | 35.5 | 78.1 | -70 | -40 |
| 19 | 44.3 | 69.1 | 34.5 | 70.7 | -55 | 60 |
| 20 | 43.5 | 64.4 | 35.0 | 70.9 | -100 | -20 |
| N | 51.4 | 72.9 | 34.5 | 75.5 | -105 | 0 |
| L | 56.0 | 75.4 | 33.5 | 76.5 | -170 | -75 |
| U | 43.5 | 64.9 | 35.5 | 66.9 | -70 | 10 |

* Average of duplicate tests of 0.357-inch-diameter specimens.

Table V Microstructure of the Investigated Plates*

| Steel | Pearlite, % | Ferrite Grain Size, ASTM No. |
|---|---|---|
| 1 | 15 | 10.0 |
| 2 | 21 | 9.5 |
| 3 | 18 | 9.9 |
| 4 | 13 | 9.7 |
| 5 | 19 | 10.1 |
| 6 | 16 | 10.2 |
| 7 | 14 | 10.1 |
| 8 | 12 | 10.1 |
| 9 | 17 | 9.5 |
| 10 | 22 | 9.3 |
| 11 | 20 | 8.8 |
| 12 | 17 | 8.4 |
| 13 | 16 | 8.7 |
| 14 | 17 | 8.2 |
| 15 | 15 | 9.2 |
| 16 | 18 | 9.5 |
| 17 | 18 | 9.5 |
| 18 | 16 | 9.2 |
| 19 | 17 | 9.0 |
| 20 | 18 | 9.3 |
| N | 23 | 8.9 |
| L | 22 | 8.5 |
| U | 17 | 8.0 |

* Determined by the quantitative television microscope.

Table VI CVN Energy, Prior Austenite Grain Size, and Hardness of the Gleeble-Treated Samples*

| | ESW Simulation | | | | 180 kJ/in. SAW Simulation | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Energy Absorbed, ft-lb | | | Prior Austenite Grain Size, | Energy Absorbed, ft-lb | | | Prior Austenite Grain Size, | Steels Selected for |
| Steel | 0°F | -40°F | Hardness, $R_B$ | ASTM No. | 0°F | -40°F | Hardness, $R_B$ | ASTM No. | Welding |
| 1 | 16 | 13(6) | 94.0 | 0.0 | 28(4) | 18(3) | 93.0 | 1.0 | |
| 2 | 21(8) | 16(4) | 85.0 | 0.0 | 26(7) | 20(2) | 90.5 | 0.5 | |
| 3 | 9 | ** | 91.0 | 0.5 | 10 | ** | 92.5 | 1.0 | |
| 4 | 12 | ** | 96.0 | 0.0 | 8 | ** | 93.0 | 0.5 | X |
| 5 | 10 | ** | 91.0 | 1.0 | ** | ** | 93.5 | 2.0 | |
| 6 | 11 | ** | 90.0 | 0.5 | 9 | ** | 94.5 | 1.0 | |
| 7 | 35(3) | 17(2) | 95.5 | 0.0 | 15 | 11 | 92.0 | 0.5 | X |
| 8 | 7 | ** | 88.0 | 1.0 | 5 | ** | 92.0 | 2.0 | |
| 9 | 10 | ** | 89.0 | 2.0 | 7 | ** | 90.5 | 2.0 | |
| 10 | 6 | ** | 93.0 | 0.0 | 8 | ** | 93.0 | 2.0 | |
| 11 | 26(7) | 9 | 93.0 | 2.5 | 11 | ** | 97.0 | 1.0 | X |
| 12 | 16 | ** | 91.0 | 0.0 | 28(4) | 13(7) | 95.0 | 2.0 | X |
| 13 | 18 | 11 | 91.0 | 0.5 | 27(6) | 12(8) | 94.0 | 1.5 | |
| 14 | 12 | ** | 89.0 | 1.0 | 18 | 7 | 92.5 | NR+ | |
| 15 | 34(5) | 12(7) | 90.0 | NR+ | 35(2) | 18(3) | 92.0 | NR+ | X |
| 16 | 35(3) | 12(7) | 95.0 | NR+ | 18 | 12(8) | 94.0 | 2.5 | |
| 17 | 34(5) | 16(4) | 90.0 | 2.0 | 25(8) | 17(5) | 91.0 | 1.5 | X |
| 18 | 73(1) | 17(2) | 95.0 | 2.5 | 32(3) | 9 | 93.0 | | X |
| 19 | 53(2) | 43(1) | 92.0 | 2.0 | 44(1) | 28(1) | 94.0 | 2.0 | X |
| 20 | 18 | 11 | 90.5 | 0.0 | 20 | 15(6) | 93.0 | 1.0 | |
| L | 6 | ** | 95.5 | 1.5 | 10 | ** | 93.5 | 1.5 | X |
| N | 31 | 8 | 89.5 | NR+ | 64 | 30 | 84.0 | 7.0 | X |
| U | 13 | ** | 86.0 | 0.0 | 16 | 8 | 92.5 | 1.5 | X |

* Parentheses indicates the energy ranking of the laboratory melted steels.
** Not tested + NR means not ratable

Examples of the microstructure in the Gleeble-treated samples are shown in Figures 3 through 13 (A and B) for the 11 steels selected for welding. For the Gleeble-treated specimens, the samples with the finer prior austenite grain sizes usually, but not always, had the better toughness, particularly if the unratable-grain-size samples are assumed to be fine grain, which is likely to be the case.

Effect of Chemical Composition on the Toughness of Gleeble-Treated Samples

For this discussion, the toughness values of Steel 4 (the base steel) shown in Table VI (12 ft-lb at 0°F for ESW and 8 ft-lb at 0°F for SAW) will be used for comparing the toughness of the other Gleeble-treated steels. For the remainder of this discussion of composition, to avoid constant repetition of "toughness of the Gleeble-treated steel," the following comparison refers only to Gleeble-treated steels and their toughness values shown in Table VI.

Steel 1. This steel was considerably better than Steel 4 for the SAW simulation (28 versus 8 ft-lb at 0°F) and somewhat better for the ESW simulation. The major differences in composition between these steels are that Steel 1 contains columbium and Steel 4 contains residuals and higher nitrogen.

Steel 2. The toughness of this reference steel was considerably better than that of the base steel for both weld simulations. Steels 2 and 4 are similar except that Steel 2 contains lower nitrogen, higher sulfur, and no residual-element additions.

Steel 3. The toughness of this 0.023 percent sulfur steel was not significantly different from that of the 0.007 percent sulfur base steel.

Steel 5. The addition of calcium to this steel did not improve its toughness compared with that of Steel 4.

Steel 6. The differences between Steels 6 and 4 are that calcium and columbium were added to Steel 6 and the residual elements (Cu, Ni, Cr, and Mo) present in Steel 4 were not added to Steel 6. These differences did not result in any significant difference in toughness. A puzzling result is that the toughness of Steel 6 was lower than that of reference Steel 1 which has a very similar composition.

Steel 7. This calcium-treated, vanadium, no-added-residual steel had improved toughness especially for the ESW simulation (35 versus 12 ft-lb at 0°F).

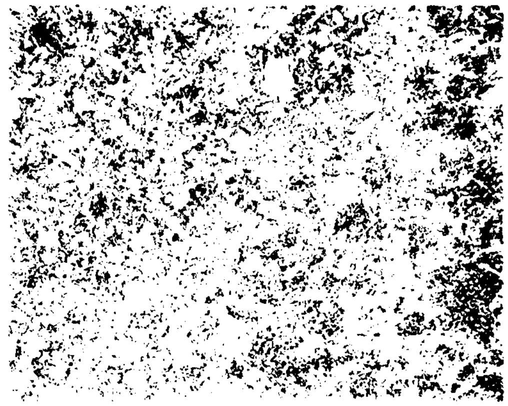
(Text continued on page 25)

Figure 3. Micrographs of Gleeble-treated and welded samples of Steel 4. Nital Etch. 40X.

A. Gleeble simulation SAW 180 kJ/inch.

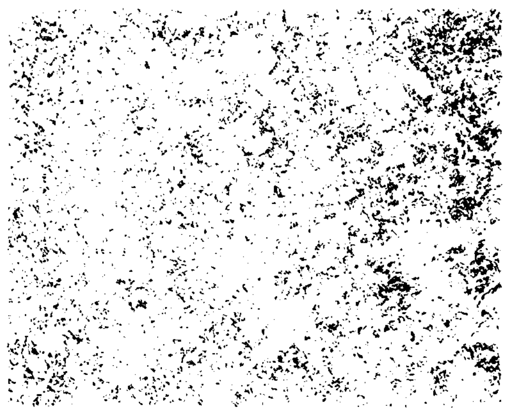
B. Gleeble simulation ESW 1000 kJ/inch.

HAZ/weld



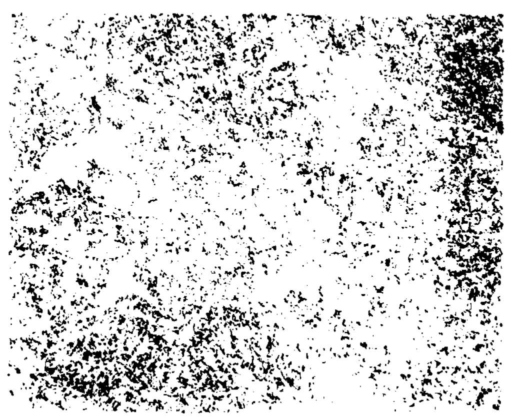
C. 75 kJ/inch SAW weld

HAZ/weld



D. 180 kJ/inch SAW weld

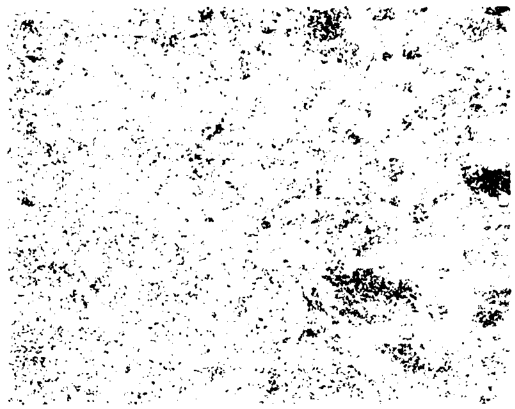
HAZ/weld



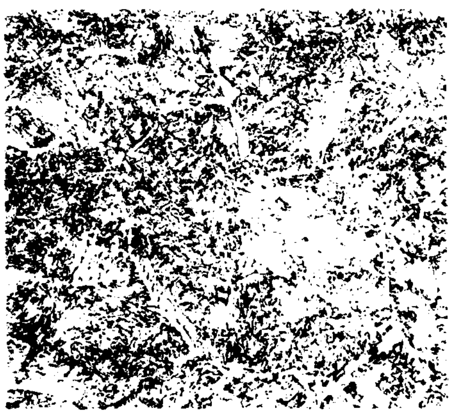
E. 1000 kJ/inch ES weld

Figure 4. Micrographs of Gleeble-treated and welded samples of Steel 7. Nital Etch. 40X.

HAZ/weld

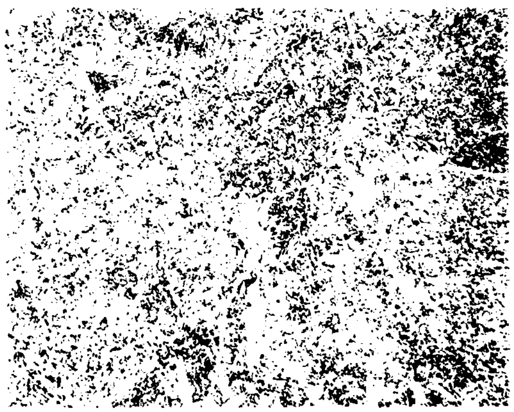


C. 75 kJ/inch SAW weld

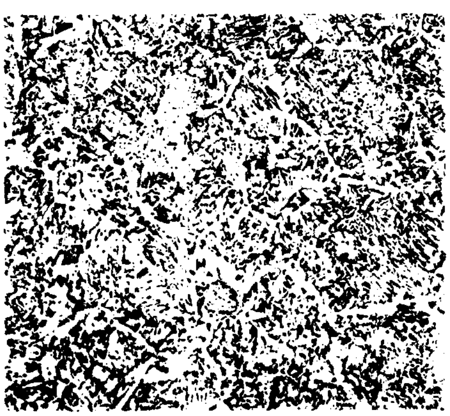


A. Gleeble simulation SAW 180 kJ/inch.

HAZ/weld

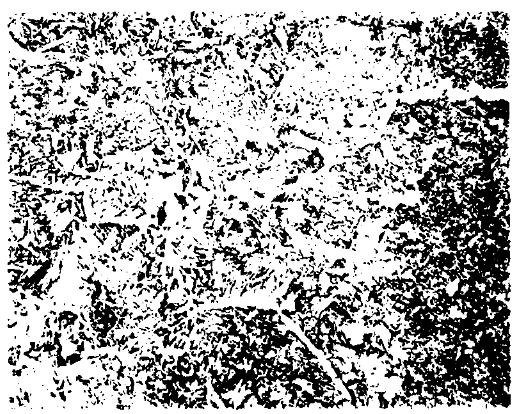


D. 180 kJ/inch SAW weld



B. Gleeble simulation ESW 1000 kJ/inch.

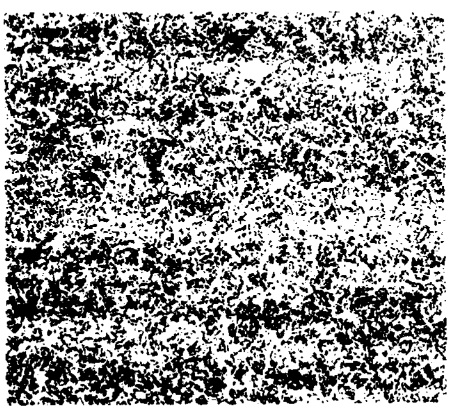
HAZ/weld



E. 1000 kJ/inch ES weld

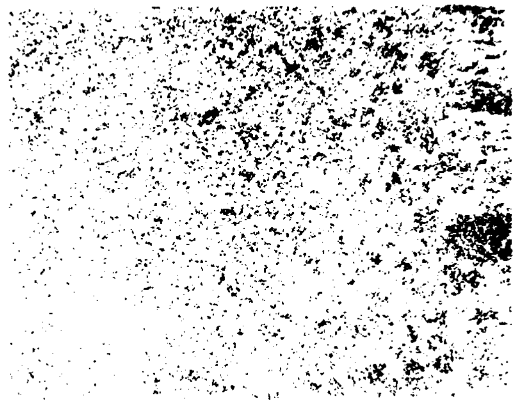
Figure 5. Micrographs of Gleeble-treated and welded samples of Steel 11. Nital Etch. 40X.

A. Gleeble simulation SAW 180 kJ/inch.



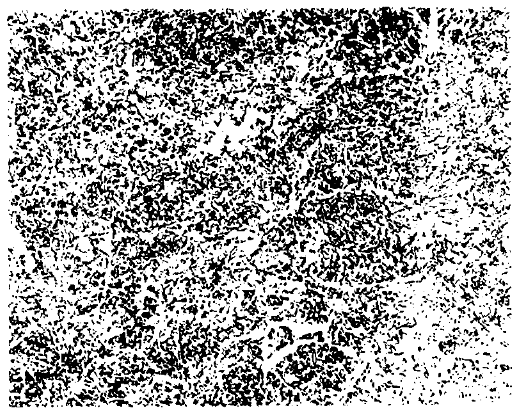
B. Gleeble simulation ESW 1000 kJ/inch.

HAZ/weld



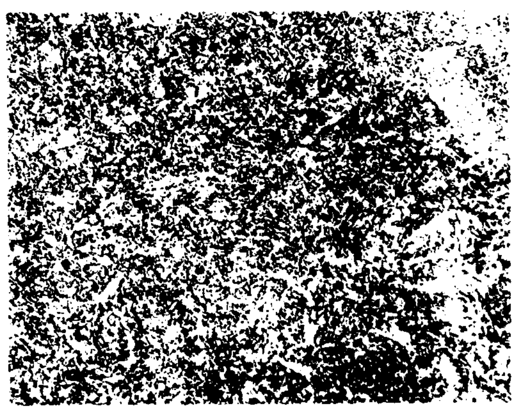
C. 75 kJ/inch SAW weld

HAZ/weld



D. 180 kJ/inch SAW weld

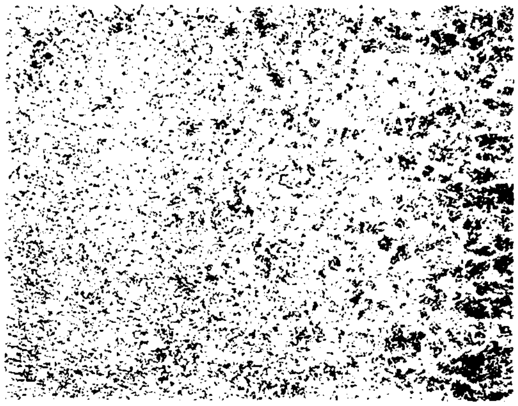
HAZ/weld



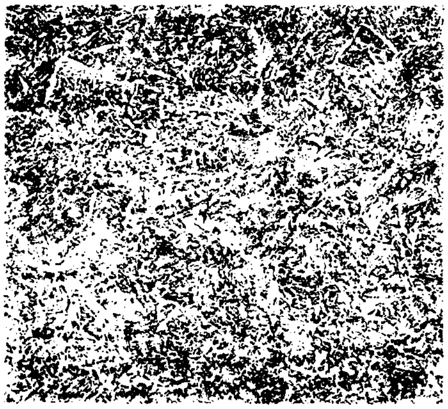
E. 1000 kJ/inch ES weld

Figure 6. Micrographs of Gleeble-treated and welded samples of Steel 12. Nital Etch. 40X.

HAZ/weld

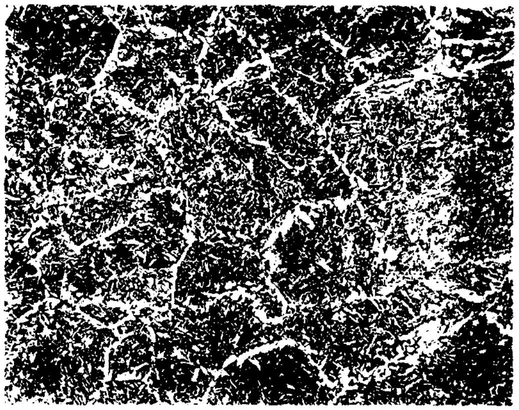


C. 75 kJ/inch SAW weld



A. Gleeble simulation SAW 180 kJ/inch.

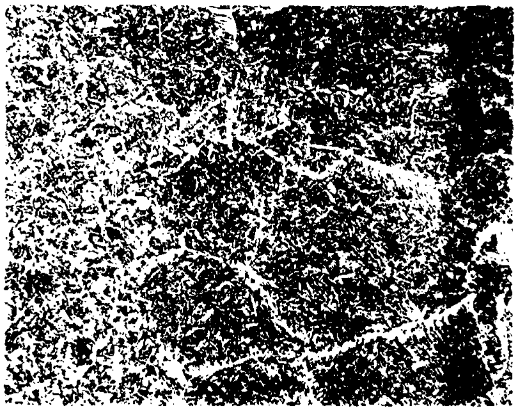
HAZ/weld



D. 180 kJ/inch SAW weld

B. Gleeble simulation ESW 1000 kJ/inch.

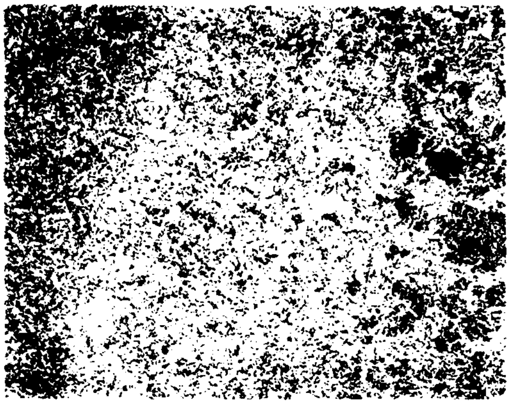
HAZ/weld



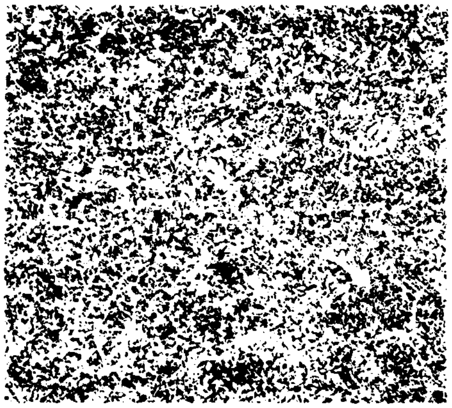
E. 1000 kJ/inch ES weld

Figure 7. Micrographs of Gleeble-treated and welded samples of Steel 15. Nital Etch. 40X.

HAZ/weld

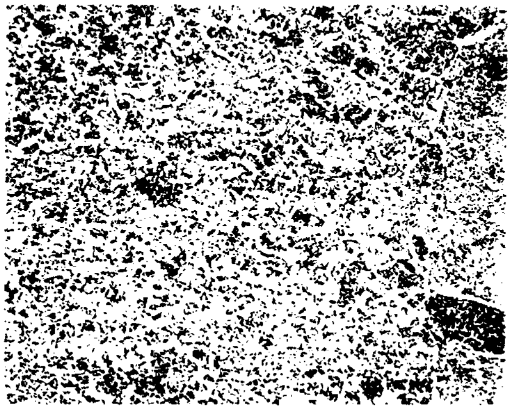


C. 75 kJ/inch SAW weld



A. Gleeble simulation
SAW 180 kJ/inch.

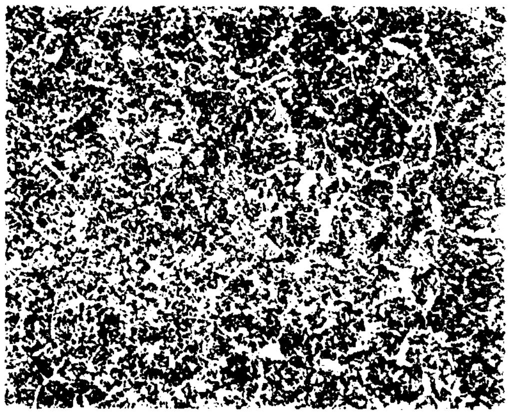
HAZ/weld



D. 180 kJ/inch SAW weld

B. Gleeble simulation
ESW 1000 kJ/inch.

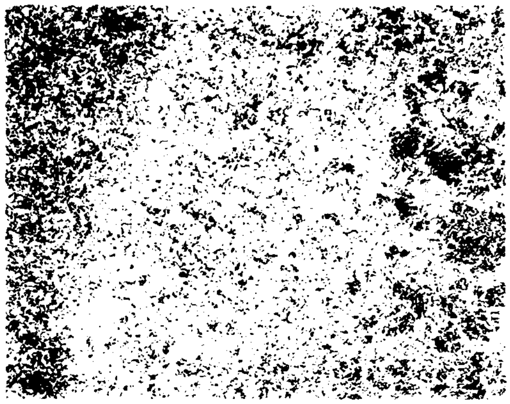
HAZ/weld



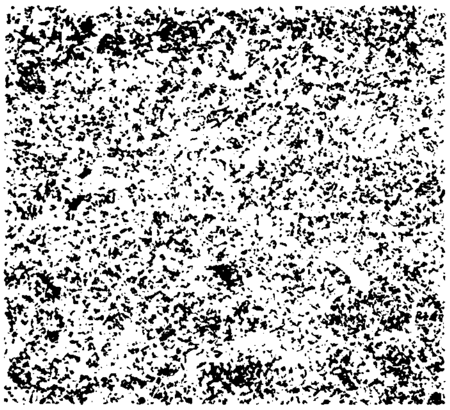
E. 1000 kJ/inch ES weld

Figure 7. Micrographs of Gleeble-treated and welded samples of Steel 15. Nital Etch. 40X.

HAZ/weld

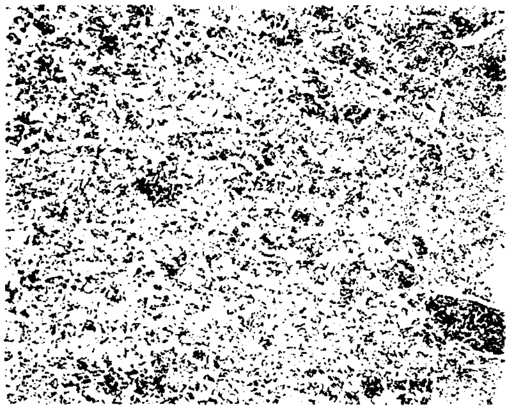


C. 75 kJ/inch SAW weld



A. Gleeble simulation SAW 180 kJ/inch.

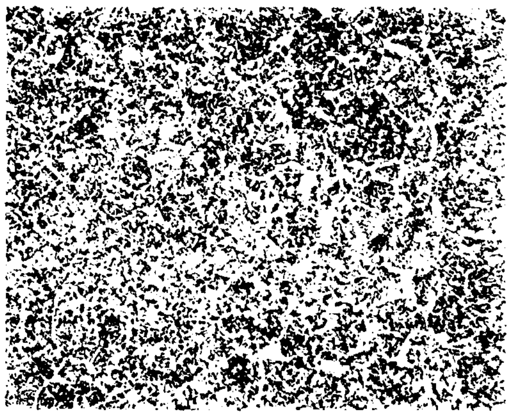
HAZ/weld



D. 180 kJ/inch SAW weld

B. Gleeble simulation ESW 1000 kJ/inch.

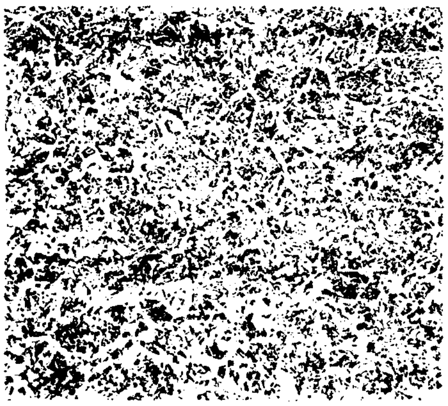
HAZ/weld



E. 1000 kJ/inch ES weld

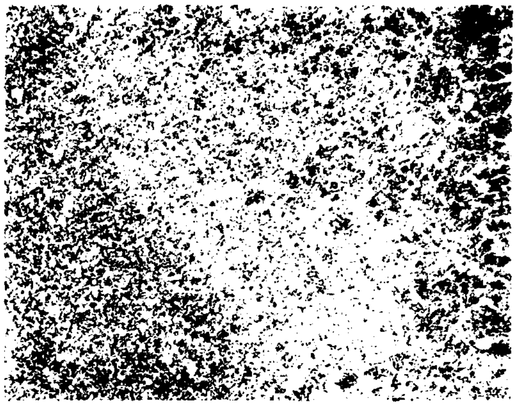
Figure 8. Micrographs of Gleeble-treated and welded samples of Steel 17 Nital Etch. 40X.

A. Gleeble simulation SAW 180 kJ/inch.



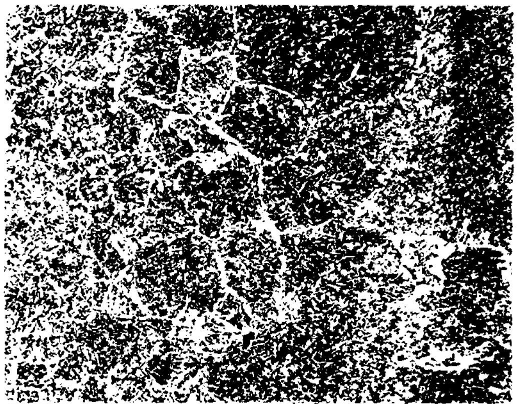
B. Gleeble simulation ESW 1000 kJ/inch.

HAZ/weld



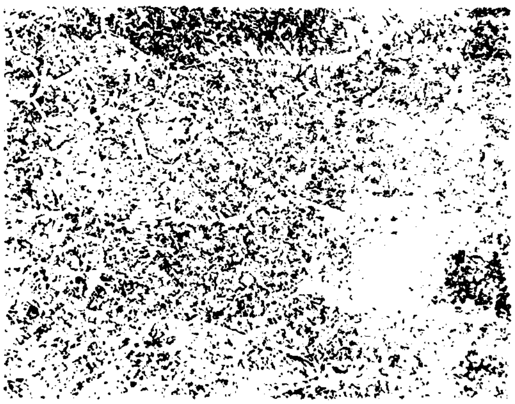
C. 75 kJ/inch SAW weld

HAZ/weld



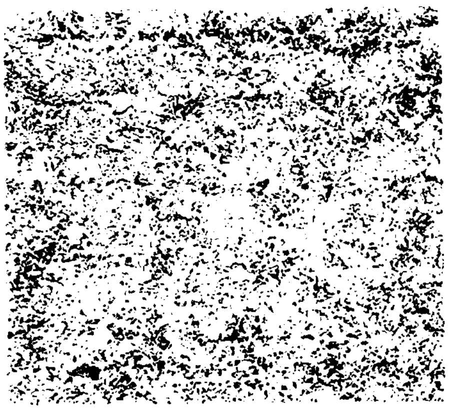
D. 180 kJ/inch SAW weld

HAZ/weld



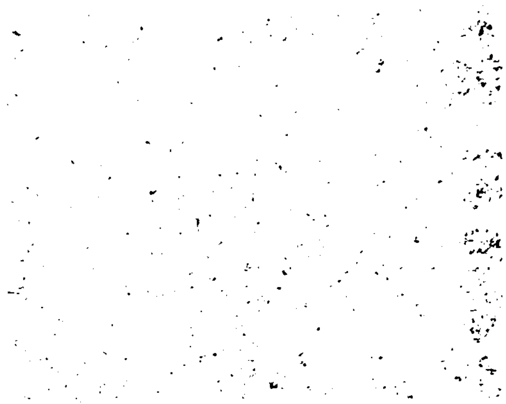
E. 1000 kJ/inch ES weld

Figure 9. Micrographs of Gleeble-treated and welded samples of Steel 18. Nital Etch. 40X.

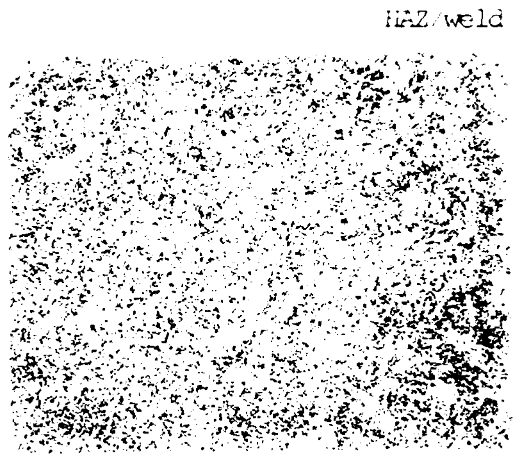


A. Gleeble simulation SAW 180 kJ/inch.

B. Gleeble simulation ESW 1000 kJ/inch.



C. 75 kJ/inch SAW weld

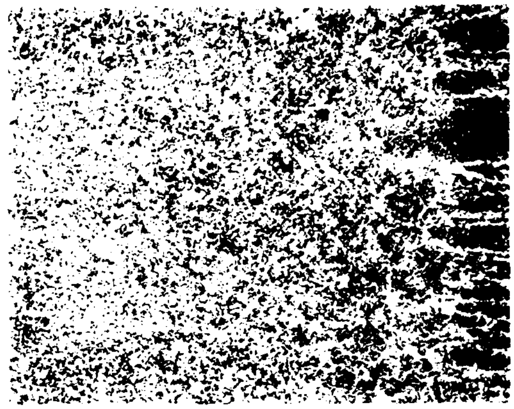



D. 180 kJ/inch SAW weld


E. 1000 kJ/inch ES weld

Figure 10. Micrographs of Gleeble-treated and welded samples of Steel 19. Nital Etch. 40X.

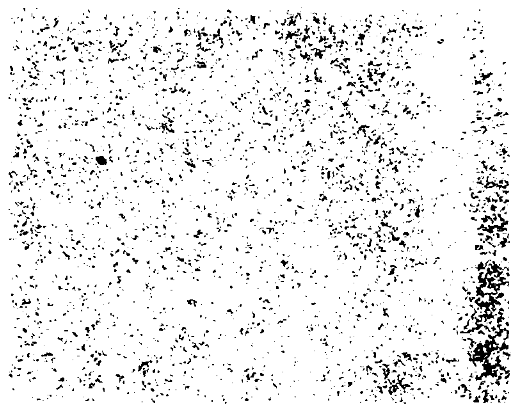
HAZ/weld



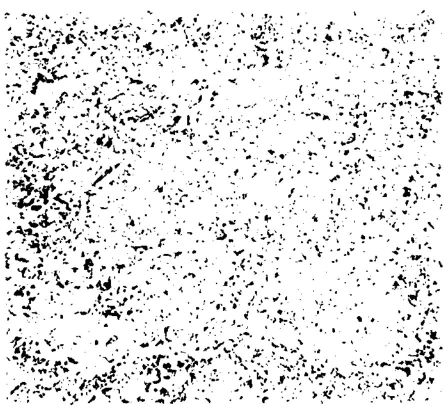
C. 75 kJ/inch SAW weld

A. Gleeble simulation SAW 180 kJ/inch.

HAZ/weld

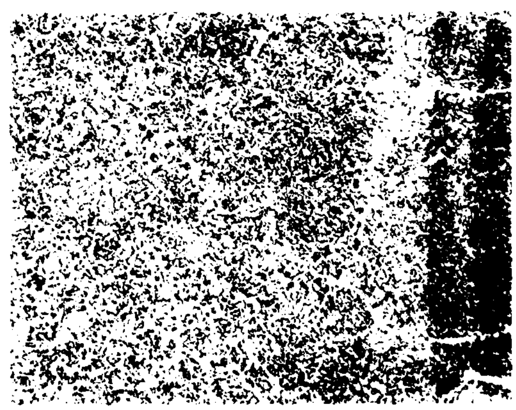


D. 180 kJ/inch SAW weld



B. Gleeble simulation ESW 1000 kJ/inch.

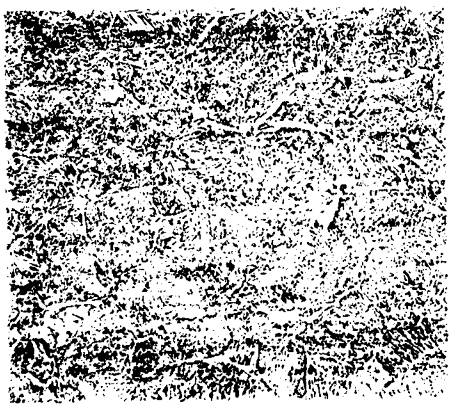
HAZ weld



E. 1000 kJ/inch ES weld

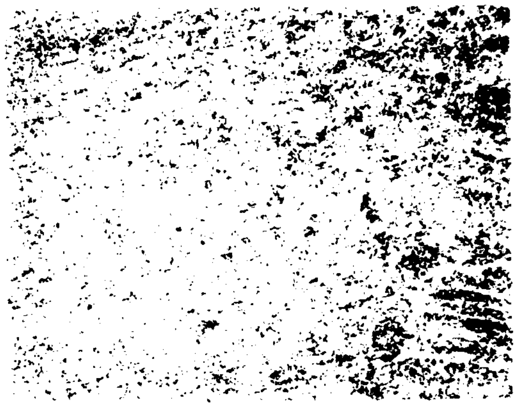
Figure 11. Micrographs of Gleeble-treated and welded samples of Steel L. Nital Etch. 40X.

A. Gleeble simulation SAW 180 kJ/inch.



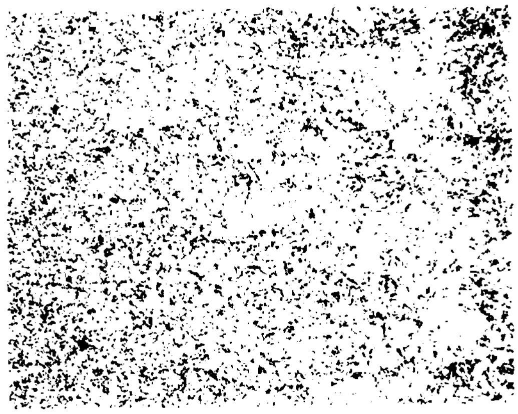
B. Gleeble simulation ESW 1000 kJ/inch.

HAZ/weld



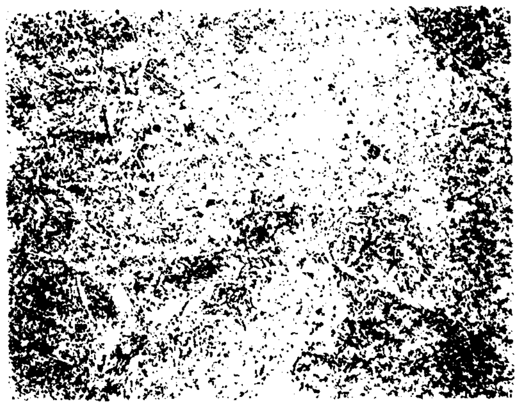
C. 75 kJ/inch SAW weld

HAZ/weld



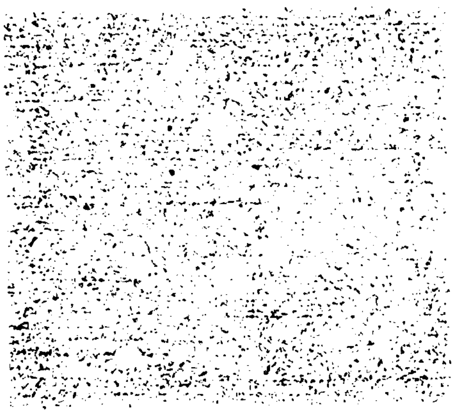
D. 180 kJ/inch SAW weld

HAZ/weld



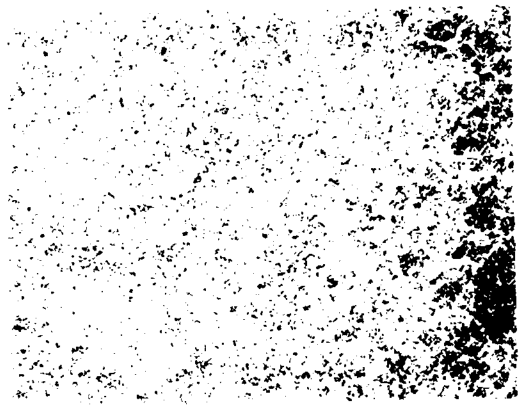
E. 1000 kJ/inch ES weld

Figure 12. Micrographs of Gleeble-treated and welded samples of Steel N. Nital Etch. 40X.

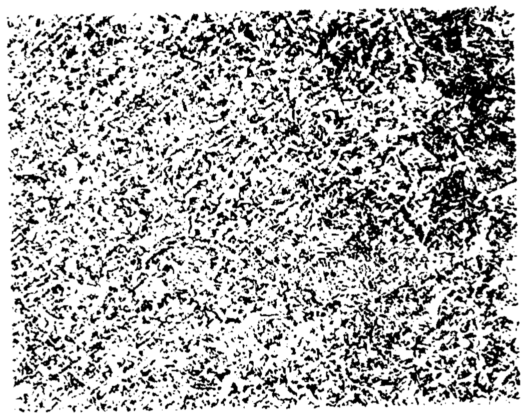


A. Gleeble simulation SAW 180 kJ/inch.

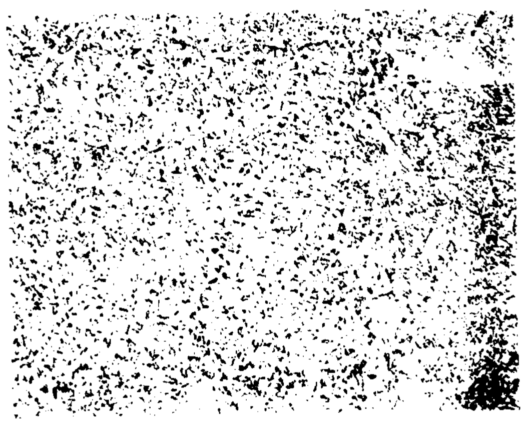
B. Gleeble simulation ESW 1000 kJ/inch.




C. 75 kJ/inch SAW weld



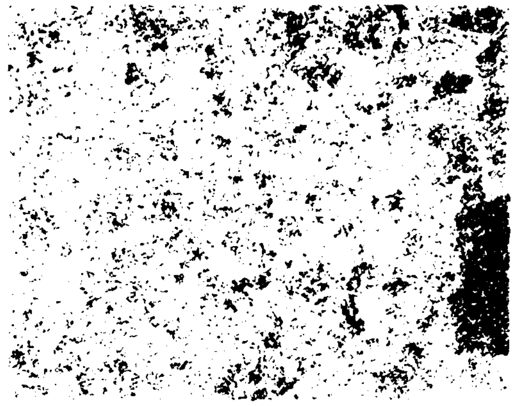

D. 180 kJ/inch SAW weld



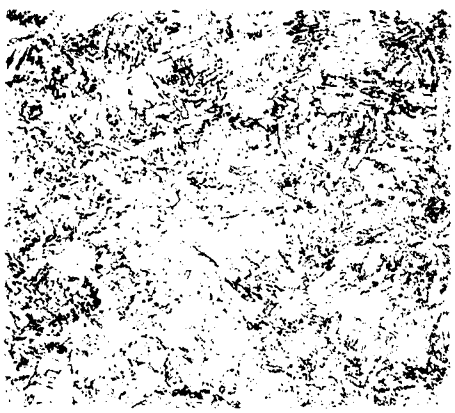

E. 1000 kJ/inch ESW weld

Figure [illegible]. Micrographs of Gleeble-treated and welded samples of Steel [illegible]. Nital Etch. 10X.

HAZ/weld

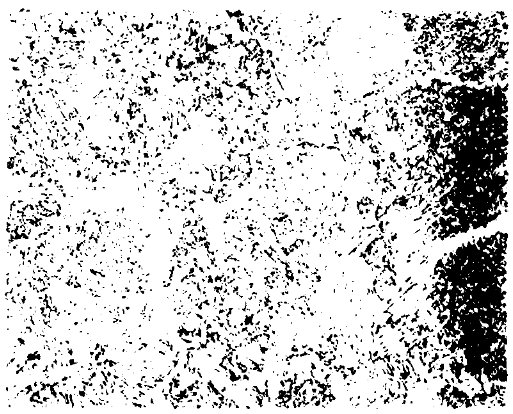


C. 75 kJ/inch SAW weld



A. Gleeble simulation
SAW 180 kJ/inch.

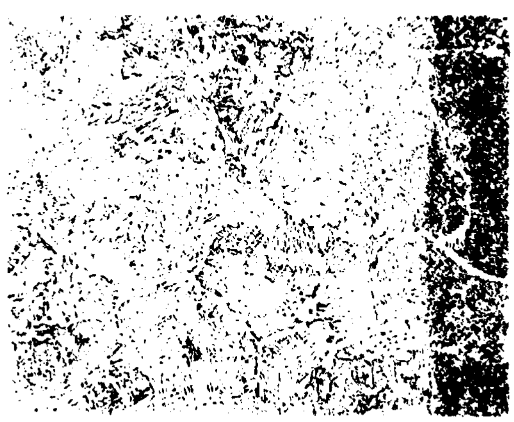
HAZ/weld



D. 180 kJ/inch SAW weld

B. Gleeble simulation
ESW 1000 kJ/inch.

HAZ/weld



E. 1000 kJ/inch ES weld

Steels 8, 9, and 10. Steels 8, 9, and 10 did not show any toughness improvement over Steel 4 for either weld simulation. All three steels contained rare-earth-metal (REM) additions, and the total REM content of the steels was approximately twice the cerium content shown in Table I. The REM additions to these steels were effective in balling the sulfides. Steel 8 also contained columbium but had no added residuals. Steels 9 and 10 contained boron.

Steel 11. This steel contained titanium in addition to a boron and REM addition. Steel 11 had about the same toughness as the base steel for the SAW simulation, but was better than the base steel for the ESW simulation (26 versus 12 ft-lb at 0°F).

Steels 12, 13, 14, and 15. These four titanium steels were heated only once for rolling, whereas all the other laboratory-melted steels were heated twice. All four steels showed some improvement over the base steel but Steel 15, which contained boron, was considerably better than Steels 12, 13, and 14, particularly for the ESW simulation. For this simulation, Steels 12, 13, 14, and 15 absorbed 16, 18, 12, and 34 ft-lb, respectively, at 0°F. Steel 14, which contained about twice as much titanium and nitrogen as Steel 13 but otherwise had the same nominal composition, had poorer toughness than Steel 13 for the SAW simulation. The difference in aluminum content between Steels 12 and 13 (0.012 versus 0.030%) did not result in any significant difference in toughness.

Steels 16, 17, 18, and 19. These four steels all had calcium additions, contained titanium, and were reheated twice for rolling. Steel 18 was REM-treated, and Steel 19 contained boron. All four of these steels had considerably better toughness than the base steel for both weld simulations and, overall, the boron-containing steel was the best of this group, as was the boron-containing steel in the group of Steels 12 through 15. Even though these steels were heated twice above 2000°F, their toughness was generally good. However, because none of the steels that were heated once had the same composition as those heated twice, no conclusion can be drawn as to the effect of reheating twice.

Steel 20. This steel did not have residual elements added, had a low silicon content (0.05%), and contained vanadium and boron. This steel had better toughness than the base steel and somewhat better toughness than the other vanadium steel in this investigation (Steel 7) for the SAW simulation, but it was not nearly as tough as Steel 7 for the ESW simulation (18 versus 35 ft-lb at 0°F).

Steels L, N, and U. Neither Steel L nor Steel U was significantly better than the base steel except that Steel U was somewhat better than the base steel for the SAW simulation (16 versus 8 ft-lb at 0°F). For the SAW simulation, Steel N was the best steel investigated, but for the ESW simulation many of the other steels in this investigation were better. This commercial steel is recommended by its producer for high-heat-input SA welds but not for ES welds.

## Welded Steels

Primarily on the basis of the toughness of the Gleeble-treated samples, and to a lesser extent of the microstructure and alloy system to which the steels belonged, eight laboratory-melted steels (Steels 4, 7, 11, 12, 15, 17, 18, and 19) were selected for welding in addition to the three commercially produced steels. These 11 steels are identified in the last column in Table VI. Although Table VI shows that Steels 1 and 2 had good toughness, these steels are laboratory-melted versions of commercial steels and were included in the investigation for information only; they were not part of the alloy investigation and thus were not selected for welding. Although the Gleeble-treated samples of Steel 4 did not have good toughness, it was the base steel in this study and was welded for comparison. Steel 16 had good toughness but was not welded because Steel 17 had somewhat better toughness and belonged to the same alloy system (Ti-N). The toughness values of the Gleeble-treated samples of Steel 11 were not very good but the microstructure of these samples was very fine and it was selected for that reason.

## Toughness of Weldments

Each of the 11 steels selected for welding was ES-welded at a heat input of about 1000 kJ/inch and SA-welded at heat inputs of 180 and 75 kJ/inch. Individual CVN test results obtained from these weldments are given in Appendix Tables D, E, and F for the ES weld and the 180 and 75 kJ/inch SA welds, respectively. Average CVN energy absorbed at 0°F (-18°C) and -40°F (-40°C) for tests at the fusion line and 1- and 3-mm HAZ locations are shown in Tables VII, VIII, and IX for these three welding processes. Parent-plate-toughness values are also shown in these tables for comparison. For each of comparison, the results from Tables VII, VIII, and IX for the 1- and 3-mm HAZ locations are shown in Table X.

ES Weldments. Referring to Table X it is apparent that the base steel (Steel 4) had the poorest toughness at the 1-mm test location of all the laboratory-melted steels that were ES-welded.

Table VII Charpy V-Notch Impact Properties of ESW Joints Investigated (Heat Input of Approximately 1000 kJ/in)

| | Energy Absorbed, ft-lb | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | at 0°F | | | | at -40°F | | | |
| Steel | Plate | FL* | 1 mm | 3 mm | Plate | FL | 1 mm | 3 mm |
| 4 | 105 | 11 | 12 | 46 | 76 | 11 | 6 | 41 |
| 7 | 106 | 28 | 63 | 62 | 76 | 13 | 33 | 60 |
| 11 | 110 | 29 | 29 | 64 | 20 | 13 | 9 | 24 |
| 12 | 65 | 20 | 38 | 46 | 44 | 21 | 18 | 27 |
| 15 | 65 | 26 | 35 | 41 | 31 | 9 | 16 | 21 |
| 17 | 81 | 22 | 53 | 51 | 55 | 29 | 17 | 15 |
| 18 | 226 | 36 | 65 | 87 | 137 | 19 | 14 | 31 |
| 19 | 52 | 42 | 45 | 50 | 24 | 13 | 35 | 44 |
| N | 121 | 65 | 44 | 91 | 96 | 34 | 8 | 70 |
| L | 163 | 32 | 9 | 7 | 133 | 10 | 5 | 8 |
| U | 40 | 27 | 24 | 30 | 25 | 20 | 11 | 16 |

* Fusion line.

Table VIII Charpy V-Notch Impact Properties of SAW Joints Investigated (Heat Input of 180 kJ/in)

| | Energy Absorbed, ft-lb | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | at 0°F | | | | at -40°F | | | |
| Steel | Plate | FL* | 1 mm | 3 mm | Plate | FL | 1 mm | 3 mm |
| 4 | 105 | 29 | 29 | 34 | 76 | 15 | 16 | 24 |
| 7 | 106 | 48 | 55 | 85 | 76 | 16 | 19 | 66 |
| 11 | 110 | 45 | 47 | 39 | 20 | 29 | 19 | 22 |
| 12 | 65 | 67 | 49 | 57 | 44 | 38 | 35 | 43 |
| 15 | 65 | 50 | 40 | 44 | 31 | 24 | 25 | 21 |
| 17 | 81 | 51 | 54 | 62 | 55 | 19 | 22 | 44 |
| 18 | 226 | 60 | 47 | 68 | 137 | 15 | 18 | 34 |
| 19 | 52 | 62 | 51 | 49 | 24 | 39 | 24 | 29 |
| N | 121 | 53 | 51 | 91 | 96 | 21 | 21 | 57 |
| L | 163 | 34 | 20 | 71 | 133 | 14 | 10 | 46 |
| U | 40 | 37 | 28 | 27 | 25 | 29 | 16 | 20 |

* Fusion line.

Table IX Charpy V-Notch Impact Properties of SAW Joints Investigated (Heat Input of 75 kJ/in)

| | Energy Absorbed, ft-lb | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | at 0°F | | | | at - 40°F | | | |
| Steel | Plate | FL* | 1 mm | 3 mm | Plate | FL | 1 mm | 3 mm |
| 4 | 105 | 53 | 69 | 73 | 76 | 34 | 26 | 44 |
| 7 | 106 | 120 | 101 | 100 | 76 | 49 | 52 | 78 |
| 11 | 110 | 81 | 76 | 28 | 20 | 65 | 23 | 8 |
| 12 | 65 | 74 | 68 | 61 | 44 | 43 | 50 | 45 |
| 15 | 65 | 66 | 59 | 43 | 31 | 45 | 37 | 33 |
| 17 | 81 | 100 | 89 | 59 | 55 | 71 | 66 | 43 |
| 18 | 226 | 121 | 133 | 117 | 137 | 89 | 75 | 63 |
| 19 | 52 | 74 | 49 | 16 | 24 | 52 | 42 | 8 |
| N | 121 | 109 | 112 | 108 | 96 | 76 | 76 | 89 |
| L | 163 | 77 | 138 | 141 | 133 | 25 | 132 | 115 |
| U | 40 | 44 | 42 | 35 | 25 | 44 | 40 | 33 |

* Fusion line.

Table X Comparison of HAZ Toughness for the Three Welding Conditions Investigated

| | CVN Energy Absorbed, ft-lb | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0°F | | | | | | | -40°F | | | | | | |
| | ESW | | SAW 180 kJ/in. | | SAW 75 kJ/in. | | Minimum Value for any Weld and Either Position | ESW | | SAW 180 kJ/in. | | SAW 75 kJ/in. | | Minimum Value for any Weld and Either Position |
| Steel | 1 mm | 3 mm | 1 mm | 3 mm | 1 mm | 3 mm | | 1 mm | 3 mm | 1 mm | 3 mm | 1 mm | 3 mm | |
| 4 | 12 | 46 | 29 | 34 | 69 | 73 | 12 | 6 | 41 | 16 | 24 | 26 | 44 | 6 |
| 7 | 63 | 62 | 55 | 85 | 101 | 100 | 55 | 33 | 60 | 19 | 66 | 52 | 78 | 19 |
| 11 | 29 | 64 | 47 | 39 | 76 | 28 | 28 | 9 | 24 | 19 | 22 | 23 | 8 | 8 |
| 12 | 38 | 46 | 49 | 57 | 68 | 61 | 38 | 18 | 27 | 35 | 43 | 50 | 45 | 18 |
| 15 | 35 | 41 | 40 | 44 | 59 | 43 | 35 | 16 | 21 | 25 | 21 | 37 | 33 | 16 |
| 17 | 53 | 51 | 54 | 62 | 89 | 59 | 51 | 17 | 15 | 22 | 44 | 66 | 43 | 15 |
| 18 | 65 | 87 | 47 | 68 | 133 | 117 | 47 | 14 | 31 | 18 | 34 | 75 | 63 | 14 |
| 19 | 45 | 50 | 51 | 49 | 49 | 16 | 16 | 35 | 44 | 24 | 29 | 42 | 8 | 8 |
| N | 44 | 91 | 51 | 91 | 112 | 108 | 44 | 8 | 70 | 21 | 59 | 76 | 89 | 8 |
| L | 9 | 7 | 20 | 71 | 138 | 141 | 7 | 5 | 8 | 10 | 46 | 132 | 115 | 5 |
| U | 24 | 30 | 28 | 27 | 42 | 35 | 24 | 11 | 16 | 16 | 20 | 40 | 33 | 11 |

These toughness comparisons will be based on the 1-mm location rather than the 3-mm location because this location generally has poorer toughness for the high-heat-input welding processes. The two steels with the best toughness at -40°F (-40°C) for the 1-mm position were Steels 7 (vanadium steel) and 19 (titanium-boron steel). It should be noted, however, that at the -40°F test temperature the base-plate toughness of the vanadium steel was about triple that of the titanium-boron steel. Four other titanium steels (12, 15, 17, and 18) had considerably better toughness than that of the base steel at the 1-mm location.

180 kJ/inch SA Weldments. All the laboratory-melted steels had reasonably good HAZ toughness for the 180 kJ/inch welds, as shown in Table X. Steels 7 and 19, which had the best HAZ toughness for the ES weld, had good HAZ toughness for this weld, but were not the best. The highest toughness steel at -40°F (35 ft-lb) for this weld condition was Steel 12, the titanium steel that was only reheated once for rolling.

75 kJ/inch SA Weldments. All the steels welded had good HAZ toughness for the 75 kJ/inch heat input SA welds except Steels 11 and 19 at the 3-mm position. Both these steels contained titanium and boron. The low toughness of Steel 19 at the 3-mm position would be a serious deterrent to the use of this titanium-boron steel even though it had very good HAZ toughness when ES-welded because any steel selected for high-heat-input welding should also be suitable for more typical heat inputs.

Hardness of Weldments. Hardness measurements were made in the base plate, weld metal, and the 1- and 3-mm locations in the HAZ for all the weldments, and are shown in Appendix Table G. No correlation was found between HAZ hardness and toughness.

Overall HAZ Toughness for all Welding Conditions. To be usable for ship construction, a steel must be weldable under typical heat inputs. In Table X, minimum CVN energy values for 0 and -40°F test temperatures for any of the three welding conditions are shown. The steel having the highest toughness (19 ft-lb) for its worst test location is Steel 7. For the -40°F test temperature, four titanium steels—Steels 12, 15, 17, and 18—are nearly as tough (14 to 18 ft-lb).

## Comparison of Toughness of Weld HAZ With Gleeble-Treated Samples

Table XI shows results of CVN tests of Gleeble-treated samples side-by-side with results from weld HAZ CVN tests at the 1-mm position. Actually, the thermal cycles of the Gleeble-treated specimens are representative of a zone closer to the fusion line

Table XI CVN Energy Absorption (ft-lb) of Gleeble-Treated Samples and HAZ of Welds at 1-mm Position

| | ES Weld | | | | SA Weld | | | |
|---|---|---|---|---|---|---|---|---|
| | 0°F (-18°C) | | -40°F (-40°C) | | 0°F | | -40°F | |
| Steel | Gleeble Simulation | Weldment | Gleeble Simulation | Weldment | Gleeble Simulation | Weldment | Gleeble Simulation | Weldment |
| 4 | 12 | 14 | * | 7 | 8 | 29 | * | 16 |
| 7 | 35 | 58 | 17 | 33 | 15 | 56 | 11 | 22 |
| 11 | 26 | 29 | 9 | 11 | 11 | 47 | * | 19 |
| 12 | 16 | 38 | * | 19 | 28 | 51 | 13 | 34 |
| 15 | 34 | 34 | 12 | 17 | 35 | 42 | 18 | 24 |
| 17 | 34 | 49 | 16 | 19 | 25 | 54 | 17 | 26 |
| 18 | 73 | 70 | 17 | 15 | 32 | 46 | 9 | 18 |
| 19 | 53 | 46 | 43 | 34 | 44 | 51 | 28 | 25 |
| L | 6 | 9 | * | 5 | 10 | 20 | * | 10 |
| N | 31 | 44 | 8 | 8 | 64 | 51 | 30 | 21 |
| U | 13 | 24 | * | 11 | 16 | 28 | 8 | 16 |

* Not tested.

than 1 mm, but fusion-line test specimens from the weldments generally extend into the weld metal so that the 1-mm location test specimen would be expected to be more like the Gleeble-treated specimens.

Considering the scatter in the data, which is apparent in the Appendix tables where individual test results are reported, the results shown in Table XI for the ES weldment and the Gleeble simulation are surprisingly close. For the SA weld, the results for the two techniques are not nearly as close, and usually the weldment tests yielded higher toughness values. This poorer agreement between weldment tests and Gleeble samples is to be expected because of the geometry of the fusion zone in this two-pass weld, which was never perpendicular to the plate surface at the notch location. An example of the position and length of the notch in a CVN specimen at the 1-mm HAZ location is shown in Figure 14B for a typical 180 kJ/inch SA weld used in this investigation. Figures 14A and 14C are typical weldments for the 75 kJ/inch SA and ES weld conditions.

## Microstructure of Weldments

Micrographs of the HAZ region of the weldments are given in Figures 3 through 13 (C, D, and E) for each of the 11 steels welded. In each micrograph of the weldments, the weld metal is on the right side and the bond line is about one-half inch from the right side of the micrograph. Generally, the micrographs of the Gleeble-treated samples show a microstructure similar to that in the weld HAZ near the bond line.

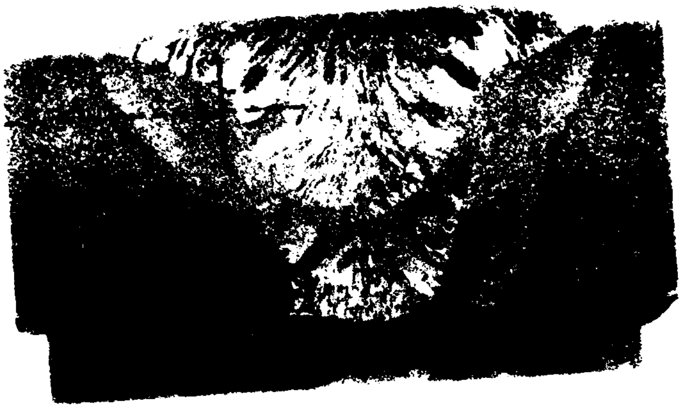
Finer details of the microstructure in the HAZ are shown in Figure 15 for the ES weldments and in Figure 16 for the 180 kJ/inch SA weldments. The HAZs of several of the weldments contain numerous small grains of martensite, examples of which are indicated by the arrows on the micrographs of Figures 15A for Steel 4 and 15C for Steel 11. Although the HAZs with large amounts of the martensite tend to have poorer toughness than the martensite-free ones, the correlation is not very strong. For example, Steel 19, when SA-welded, had a considerable amount of martensite in the HAZ, as shown in Figure 16H, but the HAZ had good toughness.

## Conclusions

Steel 7, the calcium-treated 0.08 percent vanadium steel with low residual content, appears to have the best combination of HAZ toughness and base-plate strength and toughness. For CVN tests at 0°F (-18°C) this steel had the best, or nearly the best HAZ

A. SAW weld. 75 kJ/inch

Vertical line shows lengths and location of 1-mm position notch in CVN specimen at t/4 thickness

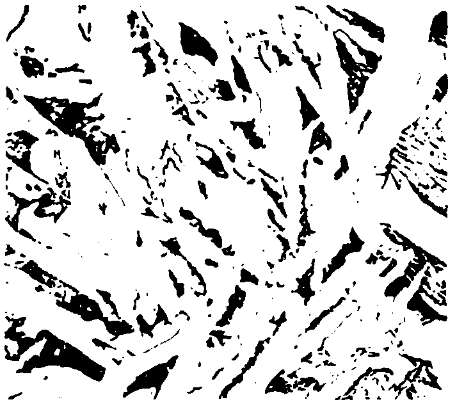


B. SAW weld. 180 kJ/inch

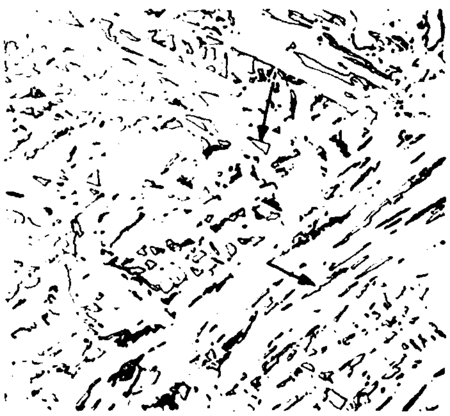
C. ES weld. 1000 kJ/inch

Figure 14. Macrographs of typical joints for the three welding conditions used

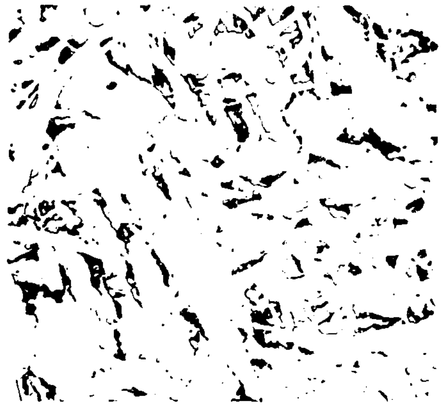
A. Steel 4



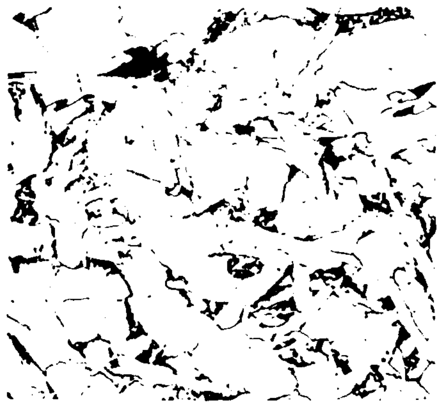
B. Steel 7



C. Steel 11



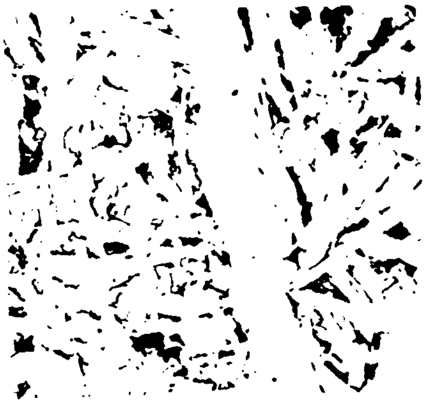
D. Steel 12



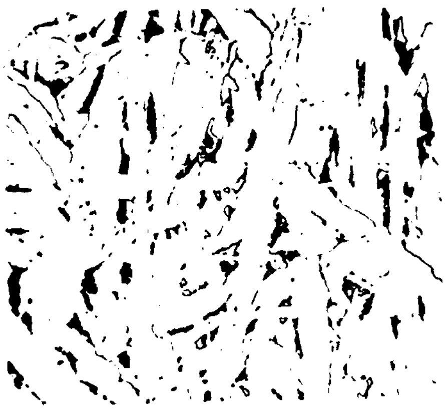
E. Steel 15

F. Steel 17

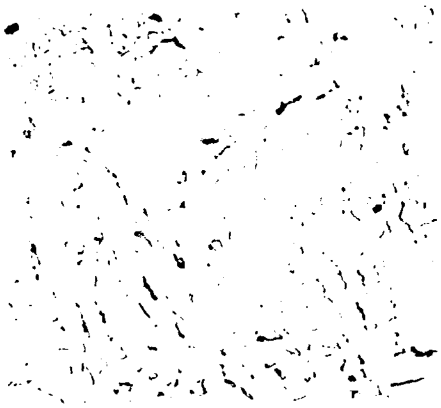
Figure 15 Micrographs of the HAZ of the ES-weldments.
Nital Etch. 800X



G. Steel 18

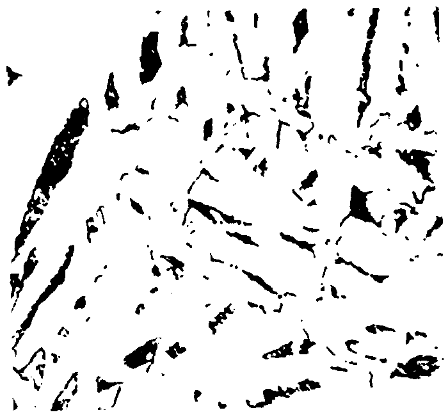


H. Steel 19



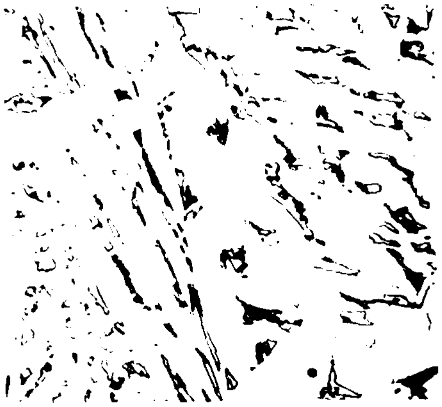
J. Steel L

I. Steel N



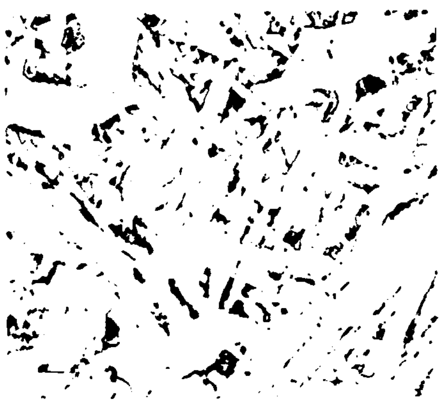
K. Steel U

Figure 15 Micrographs of the HAZ of the ES-weldments.
Nital Etch. 800X (Continued)



A. Steel 4

B. Steel 7



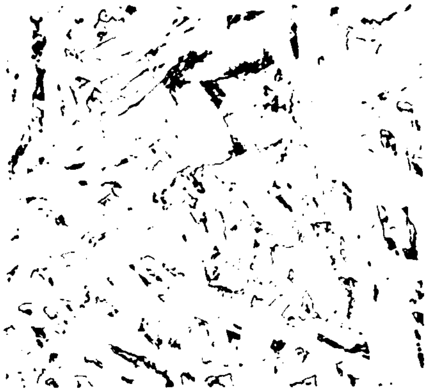
C. Steel 11

D. Steel 12

E. Steel 15

F. Steel 17

Figure 16 Micrographs of the HAZ of the 180 kJ/inch SA-weldments. Nital Etch. 800X.

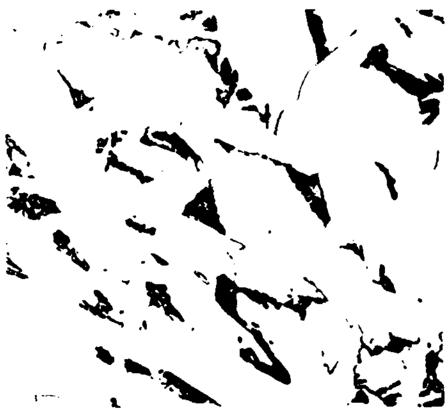


G. Steel 18

H. Steel 19

J. Steel L

I. Steel N



K. Steel U

Figure 16 Micrographs of the HAZ of the 180 kJ/inch SA-weldments. Nital Etch. 800X.

toughness for all three welding conditions used. Furthermore, the base-plate strength and toughness of this steel were substantially better than those of any of the titanium steels studied. The literature has indicated that vanadium in amounts in excess of about 0.10 percent had detrimental effects on HAZ toughness[5,6] and that about 0.06 percent vanadium may have a slightly beneficial effect.[6] Consequently, the very good HAZ toughness of Steel 7 was unexpected. The improved toughness of Steel 7 compared with the base steel may have resulted from its lower hardenability, which in turn resulted from the near absence of copper, nickel, chromium, and molybdenum in this steel (about 0.5% in the base steel).

Several of the titanium steels had very good HAZ toughness for all three welding conditions used. Two of the three titanium steels that also contained boron had very good HAZ toughness for the high-heat-input welding processes but had poor toughness at the 3-mm HAZ location for the 75 kJ/inch SA weld. The one titanium-boron steel (Steel 15) that did not exhibit this reduced toughness was reheated only once for rolling and also contained about twice as much titanium as the other two titanium-boron steels. Additionally, the titanium-boron steels had the poorest base-plate toughness of all the investigated steels so that the boron addition to these titanium steels is not an attractive method of producing a steel with improved HAZ toughness.

## References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2. Y. Kasamatsu, et al., "Study of High-Strength Steel for High Heat Input Automatic Welding," Tetsu to Hagane, Vol. 61, No. 4, 1975, Lectures 326, 327; Brutcher Translation 9968, 1975.

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APPENDIX A Individual Transverse Charpy V-Notch Test Results from the Investigated Plates

| Steel | Test Temperature, °F | Energy Absorbed, ft-lb | Shear-Fracture Appearance, % | Lateral Expansion, mils |
|---|---|---|---|---|
| 1 | 0 | 107,102,107 | 70,70,70 | 80,71,78 |
| | -40 | 81,74,90 | 50,45,50 | 66,61,69 |
| | -80 | 59,53,40 | 25,25,20 | 55,42,32 |
| | -100 | 10,30,35 | 5,10,10 | 6,21,25 |
| | -120 | 18,20,15 | 5,5,5 | 11,13,10 |
| | -140 | 9,6,6 | 5,5,5 | 4,2,5 |
| 2 | 77 | 55,60,56 | 100,100,100 | 61,66,61 |
| | 0 | 35,35,35 | 60,65,55 | 42,38,39 |
| | -20 | 25,25,26 | 35,35,40 | 30,29,31 |
| | -40 | 21,20,20 | 25,25,25 | 27,22,23 |
| | -60 | 19,20,17 | 15,15,15 | 20,20,17 |
| | -80 | 12,17,15 | 10,10,10 | 12,16,14 |
| 3 | 0 | 52,57,52 | 90,90,90 | 51,55,51 |
| | -20 | 42,51,41 | 40,55,45 | 41,49,40 |
| | -40 | 40,39,34 | 40,40,40 | 38,38,36 |
| | -80 | 28,31,25 | 15,10,15 | 27,29,24 |
| | -120 | 17,17,17 | 5,5,5 | 12,11,11 |
| | -140 | 14,16,16 | 5,5,5 | 10,11,12 |
| 4 | 0 | 98,108,108 | 60,70,60 | 75,82,79 |
| | -40 | 62,83,83 | 25,35,35 | 54,67,66 |
| | -80 | 65,50,66 | 15,10,15 | 52,41,53 |
| | -120 | 51,24,36 | 15,10,10 | 38,16,28 |
| | -140 | 35,15,9 | 10,5,5 | 23,7,5 |
| | -160 | 10,9,10 | 5,5,5 | 5,4,5 |
| 5 | 0 | 102,100,107 | 50,50,55 | 73,72,73 |
| | -80 | 52,52,68 | 20,20,25 | 42,41,54 |
| | -120 | 45,45,47 | 15,15,15 | 34,35,36 |
| | -160 | 28,28,12 | 10,10,5 | 19,19,9 |
| | -180 | 23,13,24 | 5,5,5 | 14,8,12 |
| | -200 | 6,6,5 | 5,5,5 | 7,5,5 |
| 6 | 0 | 113,170,115 | 70,65,70 | 80,81,77 |
| | -40 | 95,99,83 | 40,45,40 | 73,74,64 |
| | -80 | 70,37,58 | 35,20,25 | 59,31,47 |
| | -120 | 37,45,47 | 15,15,15 | 30,36,37 |
| | -140 | 7,18,8 | 5,5,5 | 5,13,6 |
| | -160 | 9,9,12 | 5,5,5 | 6,6,7 |
| 7 | 0 | 113,101,105 | 60,60,60 | 76,72,74 |
| | -20 | 83,84,87 | 35,40,40 | 64,64,67 |
| | -40 | 84,73,71 | 30,25,25 | 61,57,54 |
| | -80 | 75,60,57 | 20,15,15 | 61,47,46 |
| | -120 | 26,15,19 | 10,5,5 | 21,10,13 |
| | -140 | 7,18,8 | 5,5,5 | 5,13,6 |
| 8 | 0 | 226,237,221 | 100,DNB,100 | 77,DNB,82 |
| | -40 | 138,178,190 | 60,100,100 | 86,91,89 |
| | -80 | 108,112,127 | 40,45,50 | 81,91,89 |
| | -120 | 87,91,96 | 30,30,30 | 67,70,74 |
| | -140 | 82,12,18 | 25,5,5 | 66,8,11 |
| | -160 | 10,8,8 | 5,5,5 | 9,6,8 |
| 9 | 0 | 130,113,119 | 90,55,60 | 86,80,82 |
| | -80 | 72,79,74 | 25,30,25 | 58,66,61 |
| | -120 | 77,51,45 | 20,15,15 | 62,40,33 |
| | -140 | 65,45,30 | 20,15,10 | 51,38,26 |
| | -160 | 37,20,17 | 10,5,5 | 13,9,7 |
| | -180 | 10,15,15 | 5,5,5 | 7,11,9 |
| 10 | 0 | 85,87,102 | 50,55,60 | 72,70,77 |
| | -40 | 87,89,77 | 35,35,30 | 69,74,62 |
| | -80 | 39,62,60 | 10,20,20 | 33,49,47 |
| | -120 | 35,43,35 | 10,15,10 | 28,34,25 |
| | -140 | 35,26,15 | 10,10,5 | 25,20,15 |
| | -160 | 10,7,12 | 5,5,5 | 4,2,6 |
| 11 | 40 | 160,230,129 | 65,DNB,55 | 90,DNB,86 |
| | 20 | 111,117,127 | 50,50,50 | 78,82,84 |
| | 0 | 70,130,131 | 25,40,50 | 56,89,96 |
| | -40 | 16,10,35 | 5,5,10 | 17,10,19 |
| | -60 | 9,9,11 | 5,5,5 | 9,9,10 |
| | -80 | 7,9,5 | 5,5,5 | 4,6,3 |
| 12 | 77 | 107,98,100 | 99,85,90 | 81,81,81 |
| | 0 | 60,62,72 | 25,25,30 | 53,54,62 |
| | -40 | 48,35,48 | 20,15,20 | 45,35,44 |
| | -80 | 25,10,38 | 10,5,10 | 21,11,32 |
| | -100 | 10,5,9 | 5,5,5 | 7,3,6 |
| | -120 | 4,9,5 | 5,5,5 | 2,6,2 |
| 13 | 77 | 90,96,95 | 95,95,95 | 79,79,82 |
| | 0 | 43,63,59 | 25,30,30 | 43,56,53 |
| | -40 | 50,45,44 | 25,20,20 | 46,42,42 |
| | -60 | 27,19,35 | 15,10,15 | 25,20,30 |
| | -80 | 10,17,20 | 5,5,10 | 12,18,21 |
| | -100 | 7,9,11 | 5,5,5 | 6,7,8 |
| 14 | 40 | 85,95,94 | 55,60,60 | 71,76,73 |
| | 20 | 78,71,68 | 50,50,45 | 62,59,56 |
| | 0 | 55,64,55 | 25,30,25 | 48,55,49 |
| | -40 | 44,46,43 | 15,15,10 | 39,41,38 |
| | -60 | 31,23,35 | 10,10,10 | 28,21,30 |
| | -80 | 13,16,10 | 5,5,5 | 11,15,9 |
| 15 | 77 | 93,107,103 | 60,60,70 | 80,84,82 |
| | 40 | 81,75,81 | 40,40,40 | 71,64,68 |
| | 0 | 63,62,69 | 25,25,30 | 54,54,58 |
| | -40 | 22,50,20 | 15,20,15 | 25,42,21 |
| | -60 | 26,12,12 | 15,10,10 | 24,13,12 |
| | -80 | 8,9,8 | 5,5,5 | 9,10,9 |
| 16 | 77 | 121,116,115 | 70,65,65 | 85,83,83 |
| | 40 | 108,106,115 | 50,55,60 | 78,78,78 |
| | 0 | 83,63,63 | 35,25,25 | 68,52,53 |
| | -40 | 21,63,65 | 10,20,20 | 22,52,55 |
| | -60 | 11,15,18 | 5,10,10 | 11,12,16 |
| | -80 | 8,8,7 | 5,5,5 | 9,9,7 |
| 17 | 40 | 106,94,94 | 50,50,55 | 75,72,72 |
| | 0 | 83,65,94 | 40,30,45 | 68,55,74 |
| | -40 | 50,63,52 | 20,25,20 | 44,52,45 |
| | -80 | 19,31,41 | 10,15,20 | 17,26,34 |
| | -100 | 8,18,30 | 5,5,10 | 7,13,20 |
| | -120 | 5,8,4 | 5,5,5 | 1,3,1 |
| 18 | 0 | 206,234,238 | 100,DNB,DNB | 84,DNB,DNB |
| | -20 | 219,188,238 | DNB,70,DNB | DNB,90,DNB |
| | -40 | 182,102,127 | 65,35,40 | 96,78,90 |
| | -60 | 11,16,234 | 10,10,DNB | 11,15,DNB |
| | -80 | 10,14,14 | 5,5,5 | 8,12,12 |
| 19 | 77 | 81,85,86 | 50,66,60 | 71,75,75 |
| | 40 | 60,71,66 | 40,40,40 | 55,64,71 |
| | 0 | 45,60,50 | 15,20,20 | 42,52,46 |
| | -40 | 25,35,13 | 10,15,5 | 24,26,14 |
| | -60 | 9,14,11 | 5,10,10 | 9,14,12 |
| | -80 | 8,5,6 | 5,5,5 | 6,4,5 |
| 20 | 0 | 79,63,85 | 55,50,60 | 65,57,70 |
| | -20 | 83,77,68 | 55,50,45 | 67,64,58 |
| | -40 | 58,62,60 | 25,25,25 | 53,54,53 |
| | -80 | 32,43,30 | 10,15,10 | 29,36,27 |
| | -100 | 6,13,19 | 5,5,5 | 7,8,10 |
| | -120 | 13,6,6 | 5,5,5 | 7,1,1 |
| L | 0 | 147,158,185 | 100,100,100 | 87,91,96 |
| | -50 | 120,129,130 | 60,60,65 | 83,84,87 |
| | -75 | 117,117,119 | 50,50,50 | 73,75,78 |
| | -100 | 87,90,110 | 30,30,40 | 68,70,84 |
| | -150 | 15,22,54 | 5,5,15 | 11,12,38 |
| | -175 | 13,10,10 | 5,5,5 | 6,2,3 |
| N | 25 | 120,144,148 | 60,70,80 | 91,84,89 |
| | 0 | 118,121,123 | 50,50,50 | 81,82,81 |
| | -25 | 103,106,107 | 35,40,40 | 80,80,77 |
| | -50 | 89,90,91 | 30,30,30 | 64,66,68 |
| | -100 | 15,38,40 | 5,10,10 | 13,32,33 |
| | -125 | 6,6,12 | 5,5,5 | 1,2,9 |
| U | 77 | 76,73,75 | 100,100,100 | 77,73,74 |
| | 40 | 61,61,55 | 85,90,85 | 59,61,54 |
| | 0 | 36,38,45 | 35,35,45 | 40,41,45 |
| | -40 | 25,24,25 | 20,15,15 | 28,26,27 |
| | -60 | 15,20,17 | 5,10,5 | 14,20,16 |
| | -80 | 17,11,12 | 5,5,5 | 14,9,10 |

DNB means did not break

## APPENDIX B Individual Charpy V-Notch Test Results from ES-Weld-Simulation Gleeble Samples

| Steel | Test Temperature, °F | Energy Absorbed, ft-lb | Shear-Fracture Appearance, % | Lateral Expansion, mils |
|---|---|---|---|---|
| 1 | 40 | 37,46,49 | 15,20,20 | 29,39,38 |
| | 0 | 12,17,20 | 5,5,5 | 11,13,17 |
| | -20 | 16 | 5 | 12 |
| | -40 | 15,6,18 | 5,5,5 | 8,3,12 |
| 2 | 40 | 32,30 | 35,35 | 33,31 |
| | 0 | 17,24,23 | 10,10,10 | 18,25,22 |
| | -20 | 7,22 | 5,10 | 4,19 |
| | -40 | 15,15,17 | 5,5.5 | 13,13,13 |
| 3 | 77 | 30,24 | 30,25 | 32,27 |
| | 40 | 17,20,16 | 10,10.10 | 20,19,18 |
| | 20 | 11,10 | 5,5 | 12,10 |
| | 0 | 6,10,10 | 5,5,5 | 5,10,10 |
| 4 | 77 | 41,52 | 20,25 | 36,43 |
| | 40 | 18,22,19 | 15,15.10 | 19,20,18 |
| | 20 | 14,15 | 10,10 | 13,14 |
| | 0 | 11,10,15 | 5,5,5 | 10,11,14 |
| 5 | 77 | 24,29 | 15,15 | 24,32 |
| | 60 | 20,18 | 15,10 | 22,17 |
| | 40 | 12,12 | 10,10 | 13,13 |
| | 0 | 10,9,10 | 5,5,5 | 9,12,10 |
| 6 | 77 | 46,14 | 20.10 | 36,16 |
| | 40 | 23,34,30 | 10,15,15 | 18,25,22 |
| | 20 | 21,15 | 10,10 | 18,12 |
| | 0 | 15,9,8 | 5,5,5 | 13,8,6 |
| 7 | 0 | 24,41,41 | 5,15,20 | 16,30,32 |
| | -20 | 12,23 | 5,10 | 9.22 |
| | -40 | 10,19,21 | 5,5,5 | 6,12,14 |
| | -60 | 20,6 | 5,5 | 14,2 |
| 8 | 77 | 64,46 | 15,10 | 49,36 |
| | 40 | 18,18,20 | 5,5,5 | 13,13,16 |
| | 20 | 22,15 | 5,5 | 23,16 |
| | 0 | 8,6,8 | 5,5,5 | 4,5,4 |
| 9 | 77 | 50,62 | 30,35 | 43,53 |
| | 40 | 14,17,51 | 10,15,20 | 13,18,36 |
| | 20 | 15,16 | 10,15 | 15,15 |
| | 0 | 11,8,11 | 5,5,5 | 11,9,10 |
| 10 | 74 | 25,15 | 15,15 | 26,16 |
| | 74 | 12,31 | 5,15 | 13,31 |
| | 40 | 24,8,7 | 10,5,5 | 26,9,6 |
| | 0 | 6,6,6 | 5,5,5 | 6,4,6 |
| 11 | 0 | 34,18,25 | 20,10,15 | 29,17,23 |
| | -20 | 13,13 | 5,5 | 11,12 |
| | -20 | 9,11 | 5,5 | 6,10 |
| | -40 | 8,10,8 | 5,5,5 | 7,8,8 |
| 12 | 40 | 60,49 | 45,35 | 48.40 |
| | 20 | 40,39 | 25,25 | 37,36 |
| | 0 | 16,10,23 | 15,5,15 | 16,7,24 |
| 13 | 40 | 60,56 | 40,40 | 48,47 |
| | 20 | 38,45 | 25,30 | 36,39 |
| | 0 | 21,15 | 15,15 | 24,18 |
| | -40 | 11,10 | 5,5 | 11,8 |
| 14 | 60 | 30,42 | 30,35 | 31,38 |
| | 40 | 22,38 | 20,25 | 22,34 |
| | 20 | 18,20 | 20,20 | 20,21 |
| | 0 | 11,12 | 10,10 | 13,13 |
| 15 | 0 | 20,46,35 | 20,20,20 | 21,40,30 |
| | -20 | 13,14,45 | 15,15,20 | 13,14,36 |
| | -40 | 11,13,11 | 10,10,10 | 12,13,13 |
| 16 | 40 | 84,63 | 40,35 | 67.51 |
| | 0 | 14,50,40 | 10,20,20 | 14,43,37 |
| | -20 | 15,16 | 15,15 | 15.16 |
| | -40 | 10,10,15 | 10,10,10 | 11.11,15 |
| 17 | 0 | 40,27,36 | 20,15,20 | 33,23,31 |
| | -20 | 12,13 | 10,10 | 12,14 |
| | -20 | 37,9 | 20,10 | 31,9 |
| | -40 | 10,22,15 | 10,10,10 | 11,18,14 |
| 18 | 0 | 99,95,24 | 40,40,10 | 74,73,21 |
| | -20 | 80,10 | 30,10 | 63,12 |
| | -40 | 30,9,12 | 10,5,10 | 25,10,22 |
| | -60 | 11,10 | 5,5 | 11,10 |
| 19 | 0 | 60,54,44 | 35,20,15 | 53,48,43 |
| | -40 | 41,45 | 15,15 | 36,37 |
| | -60 | 20,28,22 | 10,10,10 | 19,23,20 |
| | -80 | 7,7 | 5,5 | 7,6 |
| 20 | 74 | 40,45,54 | 25,30,35 | 34,41,48 |
| | 40 | 10,11 | 5,5 | 10,13 |
| | 0 | 6,19,30 | 5,5,10 | 6,15,23 |
| | -40 | 11,10 | 5,5 | 12,9 |
| L | 100 | 13,17 | 10,10 | 16,16 |
| | 74 | 14,15,14 | 15,10,10 | 15,15,24 |
| | 40 | 9,8 | 5,5 | 8,8 |
| | 0 | 7,5,7 | 5,5,5 | 5,3,4 |
| N | 40 | 94,88 | 35,30 | 71,68 |
| | 20 | 74,60,73 | 25,20,25 | 62,52,61 |
| | 0 | 16,62,16 | 15,25,15 | 16,51,17 |
| | -40 | 6,10 | 5,5 | 7,10 |
| U | 40 | 25,30,27 | 20,20,20 | 28,30,29 |
| | 20 | 12,14,29 | 10,10,15 | 13,15,27 |
| | 0 | 22,6,10 | 10,5,5 | 21,7,9 |

APPENDIX C  Individual Charpy V-Notch Test Result from SA-Weld-Simulation Gleeble Samples

| Steel | Test Temp., °F | Energy Absorbed, ft-lb | Shear-Fracture Appearance, % | Lateral Expansion, mils |
|---|---|---|---|---|
| 1 | 20 | 53,56 | 15,15 | 38,42 |
| | 0 | 11,31,42 | 5,10,10 | 9,22,32 |
| | -40 | 10,10,35 | 5,5,10 | 10,8,24 |
| | -60 | 9,18 | 5,5 | 8,10 |
| 2 | 0 | 23,25,29 | 10,10,15 | 22,22,27 |
| | -40 | 18,19,20,21 | 5,5,5,5 | 16,17,18,20 |
| | -60 | 3,13,14 | 5,5,5 | 2,12,14 |
| 3 | RT | 25,25,28 | 15,25,15 | 29,30,28 |
| | 40 | 13,17,21 | 10,10,10 | 15,19,20 |
| | 0 | 8,9,12 | 5,5,5 | 10,11,14 |
| 4 | RT | 27,31,33,37 | 15,15,15,15 | 26,29,34,38 |
| | 40 | 15,15,16 | 10,10,10 | 17,17,18 |
| | 0 | 8,8,9 | 5,5,5 | 10,10,9 |
| 5 | RT | 39,49 | 20,25 | 35,40 |
| | 40 | 15,18,22 | 5,5,10 | 12,16,21 |
| | 20 | 12,16 | 5,5 | 12,14 |
| 6 | RT | 39,48,54 | 20,20,20 | 36,37,44 |
| | 40 | 26,26,30,46 | 10,10,10,15 | 22,22,23,37 |
| | 0 | 8,8,11 | 5,5,5 | 6,7,9 |
| 7 | 40 | 25,35 | 15,20 | 20,24 |
| | 0 | 5,6,33 | 5,5,10 | 4,6,22 |
| | -20 | 6,14,22 | 5,5,5 | 4,10,16 |
| | -40 | 7,14 | 5,5 | 5,10 |
| 8 | RT | 12,15,17,38,42 | 20,10,20,15,20 | 16,16,20,30,35 |
| | 40 | 16,20,21 | 5,10,10 | 14,17,16 |
| | 0 | 4,6 | 5,5 | 3,5 |
| 9 | RT | 26,39,39 | 20,20,25 | 36,38,36 |
| | 40 | 15,20,32,36 | 10,10,15,15 | 16,21,28,31 |
| | 0 | 6,7,9 | 5,5,5 | 8,8,9 |
| 10 | RT | 9,12,28,34 | 5,5,10,30 | 12,14,28,34 |
| | 40 | 11,13,15,25 | 5,5,5,10 | 10,12,15,22 |
| | 0 | 7,9 | 5,5 | 7,8 |
| 11 | 40 | 24,41,44 | 10,10,10 | 18,30,32 |
| | 20 | 11,32,41 | 15,10,15 | 10,24,32 |
| | 0 | 7,7,10,19 | 5,5,5,5 | 6,7,10,16 |
| 12 | 20 | 25,45 | 25,35 | 26,37 |
| | 0 | 25,31 | 10,15 | 23,27 |
| | -20 | 13,16 | 5,5 | 9,10 |
| | -40 | 12,14 | 5,5 | 12,14 |

| Steel | Test Temp., °F | Energy Absorbed, ft-lb | Shear-Fracture Appearance, % | Lateral Expansion, mils |
|---|---|---|---|---|
| 13 | 20 | 26,32 | 20,25 | 21,29 |
| | 0 | 26,28 | 15,15 | 22,25 |
| | -20 | 12,14 | 10,10 | 13,14 |
| | -40 | 7,16 | 5,5 | 5,12 |
| 14 | 20 | 24,36 | 20,25 | 21,29 |
| | 0 | 12,18,25 | 10,10,15 | 13,20,23 |
| | -40 | 6,7 | 5,5 | [illegible],6 |
| 15 | 0 | 19,39,47 | 15,20,20 | 18,33,42 |
| | -40 | 15,15,19,21 | 10,10,10,10 | 15,16,18,22 |
| | -60 | 6,8,18 | 5,5,5 | 10,10,16 |
| 16 | RT | 40,80 | 35,60 | 32,62 |
| | 40 | 59,67 | 35,40 | 44,48 |
| | 0 | 9,21,25 | 5,10,15 | 8,19,23 |
| | -40 | 11,12,12 | 5,5,5 | 12,12,12 |
| 17 | 40 | 62,63,63 | 35,35,35 | 49,49,50 |
| | 0 | 13,29,33 | 10,20,20 | 14,25,25 |
| | -40 | 13,14,19,21 | 5,5,5,5 | 14,15,17,20 |
| 18 | 40 | 80,87 | 40,40 | 54,56 |
| | 0 | 31,23,43 | 15,15,20 | 26,20,33 |
| | -20 | 19,21 | 10,10 | 16,20 |
| | -40 | 7,10,11 | 5,5,5 | [illegible],9,14 |
| 19 | 0 | 44,44 | 25,25 | 36,[illegible] |
| | -40 | 20,24,39 | 15,15,20 | 19,21,32 |
| | -60 | 9,10,27,34,36 | 5,5,5,5,10 | 10,10,24,28,30 |
| 20 | 40 | 7,42 | 5,10 | 10,32 |
| | 0 | 13,15,33 | 5,5,10 | 10,10,24 |
| | -20 | [illegible],25,27 | 5,5,5 | 2,18,18 |
| | -40 | 11,18 | 5,5 | 6,14 |
| L | 72 | 10,18,19,22,27 | 10,10,10,15,15 | 5,10,10,10,13 |
| | 40 | 11,11,14 | 5,5,5 | [illegible]6,11 |
| | 0 | 7,11,[illegible] | 5,5,5 | 5,6,8 |
| N | 0 | 60,67 | 25,25 | 49,54 |
| | -40 | [illegible],41,43 | 5,10,10 | 5,18,20 |
| | -60 | 5,5,12 | 5,5,10 | [illegible] |
| | -80 | 5,5 | 5,5 | 3,3 |
| [illegible] | 74 | 35,30 | 40,35 | 38,30 |
| | 40 | 26,27,26 | 15,15,20 | 26,27,26 |
| | 0 | 16,[illegible] | 5,5,10 | 14,[illegible],18 |
| | -40 | 3,12 | 5,5 | [illegible],9 |

APPENDIX D Individual Charpy V-Notch Data for Electroslag-Welded Steels (Heat Input of Approximately 1000 kj/in)

| Steel | Temp., °F | Energy Absorbed, ft-lb: FL | Energy Absorbed, ft-lb: 1 mm | Energy Absorbed, ft-lb: 3 mm | Shear-Fracture Appearance, %: FL | Shear-Fracture Appearance, %: 1 mm | Shear-Fracture Appearance, %: 3 mm | Lateral Expansion, mils: FL | Lateral Expansion, mils: 1 mm | Lateral Expansion, mils: 3 mm |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 0 | 11,11,16,12,7 | 15,12,26,10,8 | 50,32,60,36,37 | 5,5,5,5,5 | 10,10,15,10,10 | 30,30,35,25,25 | 11,11,16,11,9 | 11,11,16,9,11 | 42,46,52,32,41 |
| | -40 | 13,12,10,7,10 | 6,5,6,7,10 | 46,18,50,39,39 | 5,5,5,5,5 | 5,5,5,5,5 | 30,10,30,25,15 | 9,10,8,5,8 | 5,4,5,6,10 | 39,18,43,34,34 |
| 7 | 0 | 72,34,17,11,34 | 27,48,68,73,72 | 60,61,65,31,74 | 15,10,5,5,10 | 10,20,25,30,30 | 30,30,35,15,40 | 52,29,12,8,22 | 21,33,52,53,53 | 46,48,53,26,6 |
| | -40 | 38,8,7,16,14 | 43,25,46,30,20 | 69,81,65,47,45 | 10,5,5,5,5 | 10,5,10,5,5 | 20,30,20,15,15 | 29,3,3,14,13 | 30,14,34,19,12 | 54,64,47,32,36 |
| 11 | 0 | 51,22,14,21,44 | 30,34,27,25,29 | 89,42,54,76,62 | 20,10,10,10,15 | 10,10,10,10,10 | 25,15,20,25,20 | 46,20,16,20,39 | 26,28,25,22,26 | 72,34,35,60,50 |
| | -40 | 37,10,14,14,12 | 8,8,8,11,22 | 29,13,58,31,10 | 15,5,10,5,5 | 5,5,5,5,10 | 15,10,20,15,5 | 30,10,14,13,11 | 9,9,8,9,17 | 24,14,47,25,10 |
| 12 | 0 | 25,19,16,16,41 | 30,47,35,45,34 | 52,45,50,41,44 | 20,15,15,15,25 | 15,20,20,20,20 | 25,20,25,20,20 | 24,22,18,18,36 | 24,36,32,35,31 | 42,40,42,34,38 |
| | -40 | 31,9,20,28,15 | 26,11,29,11,16 | 11,31,38 | 10,5,5,10,5 | 10,5,10,5,5 | 10,15,15 | 24,10,15,23,12 | 21,9,22,11,14 | 12,28,32 |
| 15 | 0 | 21,20,33,25,32 | 38,35,41,32,33 | 46,41,40,42,34 | 25,25,25,20,25 | 20,15,20,15,15 | 25,20,20,20,20 | 20,21,28,22,25 | 33,29,34,20,28 | 25,20,20,20,20 |
| | -40 | 10,13,8,8,10 | 10,15,25,13,20 | 30,14,14,30,18 | 10,15,10,10,10 | 10,10,15,10,15 | 10,10,10,10,10 | 10,10,6,7,8 | 8,12,19,12,18 | 10,10,10,10,10 |
| 17 | 0 | 26,18,22,18,50 | 51,59,57,51,28 | 53,47,52,53,48 | 20,15,20,15,25 | 25,30,30,25,20 | 25,25,30,35,25 | 26,18,23,20,42 | 44,51,51,45,28 | 47,43,46,47,47 |
| | -40 | 30,13,32,24,34 | 34,12,11,28,10 | 14,17,26,15,10 | 20,10,20,10,35 | 10,5,5,5,5 | 10,10,15,5,5 | 26,13,26,19,32 | 28,12,12,26,10 | 15,15,26,16,11 |
| 18 | 0 | 31,31,41,36,22 | 46,93,44,110,55 | 90,74,84,100,80 | 10,25,20,15,10 | 10,30,20,35,25 | 35,25,30,50,30 | 26,41,33,31,20 | 38,70,37,81,43 | 70,60,57,78,68 |
| | -40 | 29,11,18,18,20 | 9,11,18,13,23 | 15,49,32,16,45 | 10,5,5,10,15 | 10,10,10,10,15 | 15,20,20,15,20 | 20,9,12,16,18 | 9,11,17,13,22 | 16,37,24,16,35 |
| 19 | 0 | 27,49,97,45,32 | 48,44,42,50,44 | 51,51,49,44,55 | 35,30,55,20,15 | 20,20,20,25,20 | 30,30,30,25,30 | 30,42,73,37,30 | 42,40,40,44,39 | 44,44,43,39,48 |
| | -40 | 13,30,14,11,11 | 24,34,32,41,38 | 41,50,43,48,15 | 10,15,10,5,5 | 10,10,10,10,10 | 10,15,10,15,5 | 18,25,16,10,12 | 21,30,26,35,32 | 35,40,35,40,15 |

| Steel | Temp., °F | Energy Absorbed, ft-lb: WM | Energy Absorbed, ft-lb: FL | Energy Absorbed, ft-lb: 1 mm | Energy Absorbed, ft-lb: 3 mm | Energy Absorbed, ft-lb: 5 mm |
|---|---|---|---|---|---|---|
| N | 40 | 70,57,54 | 90,147,57 | 79,52,91 | | |
| | 0 | 83,27,27 | 127,38,29 | 56,29,46 | 85,84,105 | 111,92,120 |
| | -40 | 19,30,15 | 17,5,80 | 7,9,8 | 81,75,53 | 116,114,87 |
| | -80 | 8,9,8 | 7,7,5 | 7,5,5 | 6,53,8 | 67,74,49 |
| | -120 | | | | 4,9,11 | 9,30,15 |
| L | 75 | 50,39,77 | 85,94,87 | 33,14,43 | 34,16,17 | |
| | 40 | 38,49,70 | 66,16,114 | 10,21,16 | 8,32,20 | |
| | 0 | 26,30,20 | 7,34,36 | 9,8,10 | 10,7,5 | 167,144,164 |
| | -40 | 15,12,25 | 11,15,5 | 4,6,5 | 5,10,8 | 170,131,171 |
| | -80 | | | | | 90,91,105 |
| | -120 | | | | | 52,11,72 |
| U | 40 | 36,40,55 | 31,36,44 | 22,23,21 | 33,41,36 | 42,42,52 |
| | 0 | 25,18,27 | 46,25,10 | 22,22,28 | 21,38,31 | 32,30,34 |
| | -40 | 12,11,11 | 20,20,21 | 12,10,12 | 18,15,14 | 24,26,20 |
| | -80 | 6,6,5 | 6,8,4 | 5,5,5 | 6,8,5 | 11,9,13 |

| Steel | Temp., °F | Shear-Fracture Appearance, %: WM | Shear-Fracture Appearance, %: FL | Shear-Fracture Appearance, %: 1 mm | Shear-Fracture Appearance, %: 3 mm | Shear-Fracture Appearance, %: 5 mm |
|---|---|---|---|---|---|---|
| N | 40 | 50,45,45 | 35,75,25 | 30,25,30 | | |
| | 0 | 50,20,20 | 50,20,15 | 25,15,20 | 40,40,50 | 50,50,75 |
| | -40 | 15,20,10 | 10,5,40 | 5,5,5 | 35,30,20 | 50,50,35 |
| | -80 | 10,10,10 | 5,5,5 | 5,5,5 | 5,15,5 | 20,20,15 |
| | -120 | | | | 5,5,5 | 5,10,5 |
| L | 75 | 50,60,65 | 65,70,65 | 15,10,20 | 20,10,10 | |
| | 40 | 30,35,60 | 50,10,65 | 10,10,10 | 5,35,10 | |
| | 0 | 20,20,15 | 5,40,20 | 5,5,10 | 5,5,5 | 100,100,100 |
| | -40 | 15,15,15 | 10,5,5 | 5,5,5 | 5,5,5 | 100,90,100 |
| | -80 | | | | | 35,40,80 |
| | -120 | | | | | 20,5,30 |
| U | 40 | 40,40,45 | 15,25,20 | 25,20,15 | 20,45,40 | 60,55,70 |
| | 0 | 20,15,20 | 15,10,10 | 10,10,10 | 10,15,30 | 30,25,30 |
| | -40 | 10,10,10 | 5,5,5 | 5,5,5 | 5,5,5 | 20,20,15 |
| | -80 | 5,5,5 | 5,5,5 | 5,5,5 | 5,5,5 | 5,5,5 |

| Steel | Temp., °F | Lateral Expansion, mils: WM | Lateral Expansion, mils: FL | Lateral Expansion, mils: 1 mm | Lateral Expansion, mils: 3 mm | Lateral Expansion, mils: 5 mm |
|---|---|---|---|---|---|---|
| N | 40 | 55,40,45 | 66,92,46 | 68,45,76 | | |
| | 0 | 61,25,27 | 85,38,29 | 51,30,42 | 72,72,78 | 82,70,80 |
| | -40 | 22,26,15 | 14,5,55 | 8,10,9 | 67,64,47 | 83,82,71 |
| | -80 | 5,5,5 | 5,7,4 | 4,4,3 | 6,41,7 | 54,57,38 |
| | -120 | | | | 4,5,6 | 7,20,9 |
| L | 75 | 47,52,60 | 70,73,67 | 28,14,38 | 27,18,20 | |
| | 40 | 33,38,53 | 51,13,82 | 10,19,18 | 8,28,17 | |
| | 0 | 25,25,19 | 6,44,31 | 6,5,8 | 9,4,2 | 91,94,92 |
| | -40 | 15,13,23 | 12,17,4 | 2,5,5 | 6,12,6 | 98,85,92 |
| | -80 | | | | | 71,72,80 |
| | -120 | | | | | 40,10,55 |
| U | 40 | 35,36,45 | 28,48,34 | 23,24,20 | 29,37,35 | 42,43,53 |
| | 0 | 24,18,25 | 36,14,10 | 19,23,22 | 18,33,30 | 31,30,34 |
| | -40 | 11,10,10 | 12,12,13 | 8,10,8 | 13,11,9 | 24,25,17 |
| | -80 | 5,5,4 | 5,6,2 | 5,4,2 | 3,5,3 | 9,7,9 |

APPENDIX E Individual Charpy V-Notch Data for Submerged-Arc Welded Steels (Heat Input of 180 kJ/in)

| Steel | Temp., °F | Energy Absorbed, ft-lb FL | Energy Absorbed, ft-lb 1 mm | Energy Absorbed, ft-lb 3 mm | Shear-Fracture Appearance, % FL | Shear-Fracture Appearance, % 1 mm | Shear-Fracture Appearance, % 3 mm | Lateral Expansion, mils FL | Lateral Expansion, mils 1 mm | Lateral Expansion, mils 3 mm |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 0 | 24,30,28,29,55 | 25,31,33,30,26 | 33,53,28,34,34 | 30,30,35,30,50 | 35,35,40,40,35 | 35,50,35,40,45 | 21,26,26,25,44 | 23,28,32,28,24 | 29,44,27,30,31 |
| | -40 | 21,16,15,15,15 | 12,20,13,19,17 | 25,25,23,21,23 | 20,15,15,15,15 | 10,15,10,20,15 | 25,25,25,25,25 | 20,18,15,17,15 | 13,20,12,19,18 | 25,24,24,20,24 |
| 7 | 0 | 60,28,30,71,54 | 79,81,42,33,43 | 91,77,86,86,83 | 30,15,15,35,30 | 40,45,20,25,30 | 40,35,40,50,40 | 46,23,26,53,44 | 59,60,33,30,37 | 73,53,67,65,67 |
| | -40 | 38,11,13,15,20 | 17,18,21,36,16 | 65,66,44,68,78 | 20,10,10,10,15 | 20,20,20,25,20 | 25,25,20,30,30 | 30,8,10,12,18 | 17,14,17,27,13 | 52,49,38,52,63 |
| 11 | 0 | 65,43,44,42,49 | 41,47,59,35,52 | 40,63,25,25,51 | 45,35,35,35,40 | 40,45,50,40,45 | 30,35,25,25,30 | 54,36,35,33,39 | 33,37,46,28,41 | 33,46,26,24,39 |
| | -40 | 38,13,31,21,36 | 24,13,15,24,17 | 24,20,12,21,29 | 20,15,15,20,20 | 20,15,15,20,15 | 20,20,20,20,20 | 35,15,29,22,32 | 21,15,17,22,18 | 21,19,14,20,24 |
| 12 | 0 | 79,60,74,68,51 | 45,52,50,32,74 | 25,63,52,56,62 | 40,45,45,45,30 | 30,30,30,25,50 | 30,40,35,35,40 | 62,54,58,56,42 | 38,43,43,28,68 | 26,50,4[illegible],[illegible],52 |
| | -40 | 40,41,13,32,44 | 16,47,36,25,45 | 56,47,17,46,35 | 20,20,15,20,20 | 15,20,20,15,20 | 25,20,15,20,20 | 33,32,14,29,37 | 15,38,32,23,37 | 46,41,18,[illegible] |
| 15 | 0 | 46,56,48,47,54 | 49,38,40,41,40 | 39,52,48,31,45 | 40,50,35,45,50 | 35,40,30,30,35 | 35,40,40,30,40 | 39,46,40,42,44 | 42,32,33,34,32 | 34,43,41,26,38 |
| | -40 | 32,21,15,20,35 | 25,25,20,27,24 | 28,23,18,22,15 | 20,15,10,20,20 | 20,20,15,20,15 | 20,20,15,20,15 | 29,19,16,20,28 | 22,20,18,22,21 | 23,22,17,20,1[illegible] |
| 17 | 0 | 35,55,50,49,71 | 43,33,65,73,54 | 63,73,61,62,53 | 30,40,40,40,50 | 35,30,35,40,35 | 40,50,35,35,30 | 30,46,39,41,54 | 35,31,45,55,40 | 47,59,48,48,40 |
| | -40 | 18,25,17,18,22 | 25,20,45,19,22 | 48,47,45,41,35 | 15,20,15,15,15 | 25,20,35,25,20 | 25,25,25,20,15 | 18,24,16,19,20 | 22,20,38,21,20 | 38,36,35,35,30 |
| 18 | 0 | 60,56,88,63,43 | 56,25,27,64,59 | 118,26,70,60,73 | 35,30,40,35,25 | 25,15,15,30,30 | 50,20,35,30,35 | 30,46,66,50,37 | 46,23,26,50,48 | 84,26,56,48,58 |
| | -40 | 14,19,14,13,17 | 16,15,21,23,16 | 40,38,17,53,25 | 15,20,15,20,20 | 20,20,25,25,20 | 25,25,15,25,15 | 17,18,13,13,17 | 14,15,20,22,15 | 36,30,16,39,19 |
| 19 | 0 | 46,64,82,70,52 | 52,50,45,51,55 | 56,40,50,50,47 | 55,60,70,60,50 | 50,50,45,50,50 | 50,45,45,35,35 | 48,55,67,62,48 | 47,46,40,42,49 | 49,38,43,41,4[illegible] |
| | -40 | 36,42,39,35,42 | 28,33,22,19,21 | 35,20,40,21,30 | 25,30,25,20,25 | 25,25,25,25,25 | 25,20,30,30,20 | 36,38,37,30,37 | 27,28,23,22,23 | 31,20,35,21,26 |

| Steel | Temp., °F | Energy Absorbed, ft-lb WM | Energy Absorbed, ft-lb FL | Energy Absorbed, ft-lb 1 mm | Energy Absorbed, ft-lb 3 mm | Energy Absorbed, ft-lb 5 mm | Shear-Fracture Appearance, % WM | Shear-Fracture Appearance, % FL | Shear-Fracture Appearance, % 1 mm | Shear-Fracture Appearance, % 3 mm | Shear-Fracture Appearance, % 5 mm | Lateral Expansion, mils WM | Lateral Expansion, mils FL | Lateral Expansion, mils 1 mm | Lateral Expansion, mils 3 mm | Lateral Expansion, mils 5 mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M | 75 | 65,41,87 | | | | | 45,30,60 | | | | | 59,39,68 | | | | |
| | 40 | 35,37,51 | 101,55,117 | 83,114,112 | 96,75,106 | | 25,30,40 | 60,35,65 | 50,60,60 | 50,60,60 | | 31,33,43 | 77,45,83 | 63,80,77 | 73,62,77 | |
| | 0 | 34,32,24 | 64,69,27 | 66,33,55 | 93,104,75 | 120,153,117 | 25,20,15 | 35,40,20 | 30,20,35 | 40.60,40 | 65,100,70 | 31,28,19 | 53,52,27 | 51,32,44 | 72,77,58 | 80,91,76 |
| | -40 | 11,7,21 | 11,11,40 | 21,20,21 | 85,38,39 | 68,84,58 | 10,5,10 | 10,10,20 | 15,15,10 | 35,20,20 | 30,35,30 | 9,21,31 | 14,15,33 | 22,21,21 | 71,33,35 | 53,66,47 |
| | -80 | | 16,7,10 | 11,13,13 | 37,18,13 | 67,60,111 | | 20,5,5 | 10,10,10 | 20,15,10 | 20,20,35 | | 17,9,9 | 11,13,13 | 30,16,13 | 54,50,80 |
| | -120 | | | | | 5,6,7 | | | | | 5,5,5 | | | | | 5,6,8 |
| L | 75 | 25,82,44 | 61,90,69 | 37,87,115 | | | 35,90,50 | 50,75,50 | 45,55,60 | | | 33,72,42 | 50,68,54 | 22,61,78 | | |
| | 40 | 25,24,11 | 39,39,42 | 43,24,31 | 147,101,109 | 141,165,165 | 20,20,15 | 30,30,30 | 50,35,35 | 70,55,65 | 75,100,100 | 22,20,13 | 30,36,38 | 44,28,25 | 90,75,76 | 93,98,95 |
| | 0 | 10,10,21 | 47,16,40 | 23,17,21 | 74,40,100 | 140,140,165 | 10,5,10 | 20,10,25 | 25,20,20 | 35,25,60 | 80,80,100 | 14,13,21 | 38,16,35 | 25,19,22 | 56,37,74 | 94,95,97 |
| | -40 | 8,5,5 | 22,11,8 | 11,11,9 | 28,28,83 | 169,120,140 | 5,5,5 | 10,5,5 | 5,5,5 | 30,30,45 | 100,60,75 | 7,4,4 | 20,10,8 | 9,8,6 | 23,25,45 | 95,88,94 |
| | -80 | | | | 34,51,65 | 14,30,100 | | | | 20,20,20 | 10,10,55 | | | | 39,41,47 | 26,27,27 |
| U | 40 | 64,58,43 | 42,40,60 | 38,35,35 | 40,37,38 | 43,47,36 | 80,80,70 | 60,60,70 | 40,50,55 | 60,50,50 | 70,70,60 | 57,56,41 | 42,41,53 | 40,36,37 | 41,42,42 | 44,48,38 |
| | 0 | 32,31,37 | 34,30,47 | 27,28,28 | 26,32,24 | 23,33,32 | 20,20,25 | 30,30,35 | 30,30,30 | 30,35,20 | 20,30,35 | 31,29,28 | 35,30,44 | 30,28,30 | 30,33,30 | 27,35,35 |
| | -40 | 20,17,25 | 26,36,25 | 23,13,11 | 20,25,15 | 20,23,23 | 15,10,15 | 20,25,20 | 20,15,15 | 20,30,20 | 20,20,15 | 24,19,23 | 25,31,26 | 26,15,13 | 21,28,19 | 23,26,26 |
| | -80 | 3,13,7 | 8,9,7 | 12,7,11 | 18,9,14 | 12,15,15 | 5,10,5 | 10,10,10 | 10,10,10 | 20,10,5 | 10,15,10 | 2,13,9 | 11,9,8 | 11,7,11 | 18,10,12 | 13,14,14 |

APPENDIX F Individual Charpy V-Notch Data for Submerged-Arc Welded Steels (Heat Input of 55 kJ/in)

| Steel | Temp., °F | Energy Absorbed, ft-lb FL | Energy Absorbed, ft-lb 1 mm | Energy Absorbed, ft-lb 3 mm | Lateral Expansion, mils FL | Lateral Expansion, mils 1 mm | Lateral Expansion, mils 3 mm | Shear-Fracture Appearance, % FL | Shear-Fracture Appearance, % 1 mm | Shear-Fracture Appearance, % 3 mm |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 40,62,50,62,34 | 38,62,74,83,71 | 77,73,70,70,75 | 40,50,41,51,32 | 37,49,56,61,55 | 61,60,59,58,57 | 35,40,40,55,35 | 35,45,50,60,50 | 50,45,40,40,55 |
| | -40 | 18,43,33,26,55 | 24,27,29,25,27 | 34,40,40,40,35 | 18,37,25,21,42 | 21,24,27,22,27 | 30,39,36,42,34 | 20,35,25,20,40 | 20,25,25,25,25 | 25,35,30,35,35 |
| | 0 | 120,88,123,121,119 | 81,107,96,99,110 | 90,110,94,108,90 | 85,55,75,79,81 | 56,76,65,67,74 | 71,88,70,76,69 | 60,50,55,60,60 | 45,65,55,55,60 | 45,35,55,60,55 |
| | -40 | 11,35,104,25,66 | 33,27,51,80,71 | 77,84,72,84,70 | 13,39,66,23,50 | 31,27,38,58,54 | 64,64,57,65,55 | 20,30,45,30,35 | 35,30,35,40,45 | 35,40,35,40,30 |
| 11 | 0 | 91,108,83,64,69 | 72,61,73,95,83 | 37,26,20,13,53 | 71,70,69,55,55 | 54,46,53,65,63 | 31,22,17,14,39 | 50,50,55,45,45 | 40,35,35,60,50 | 15,10,10,5,25 |
| | 40 | 40,62,70,65,68 | 18,16,34,18,49 | 21,6,8,8,8 | 37,44,49,49,50 | 15,13,25,17,34 | 16,6,7,6,6 | 20,35,40,50,50 | 0,5,5,10,20 | 5,5,5,5,5 |
| | 0 | 75,64,78,69,92 | 86,74,60,71,53 | 67,72,60,45,55 | 54,50,53,50,65 | 60,50,43,53,41 | 50,33,47,39,45 | 35,30,35,30,55 | 45,30,40,25 | 35,40,30,20,25 |
| | -40 | 40,34,47,41,22 | 50,48,50,51,49 | 36,40,29,57,50 | 32,42,36,32,21 | 37,35,39,40,37 | 29,38,25,42,38 | 20,25,25,20,10 | 0,20,25,30,20 | 15,20,10,20,20 |
| | 0 | 101,40,58,60,71 | 59,56,62,62,48 | 44,48,43,36,43 | 73,34,41,51,53 | 46,41,47,48,38 | 36,39,34,29,34 | 70,35,40,45,50 | 40,40,45,45,40 | 25,30,25,20,25 |
| | 40 | 46,42,48,42,65 | 33,45,40,38,31 | 33,31,34,37,28 | 35,33,36,32,46 | 26,35,30,30,25 | 25,23,26,28,15 | 25,25,30,25,45 | 45,30,30,30,25 | 20,15,20,20,15 |
| | 0 | 100,97,94,108,103 | 85,87,97,95,85 | 62,57,63,56,58 | 75,72,67,78,78 | 58,63,67,65,62 | 48,47,62,47,50 | 60,55,50,60,80 | 40,40,45,45,50 | 25,35,35,30,35 |
| | -40 | 66,80,90,64,66 | 71,54,84,57,71 | 45,26,41,49,43 | 50,62,66,48,51 | 53,114,59,42,50 | 35,24,34,39,33 | 30,50,55,40,30 | 30,25,35,25,30 | 15,10,15,20,15 |
| 5 | 0 | 135,124,126,114,108 | 124,124,143,160,132 | 129,111,111,82,130 | 87,83,83,78,76 | 82,75,90,94,84 | 87,78,77,61,90 | 60,55,55,60,50 | 50,55,60,60,50 | 55,45,45,35,55 |
| | 40 | 113,92,120,21,61 | 83,77,26,141,66 | 74,62,60,54,66 | 74,65,83,24,40 | 58,53,26,97,49 | 55,48,47,41,53 | 35,35,50,45,75 | 0,35,20,50,25 | 20,20,20,20,20 |
| | 0 | 100,90,72,61,56 | 60,42,42,53,33 | 10,15,16,16,14 | 68,63,52,116,42 | 42,29,30,41,42 | 16,14,16,16,14 | 40,50,40,35,30 | 25,20,20,25,25 | 10,10,10,10,10 |
| | 40 | 52,74,35,64,41 | 44,42,40,41,42 | 9,7,8,7,11 | 37,55,26,48,34 | 30,29,27,30,31 | 7,6,7,6,9 | 10,40,20,35,25 | 25,25,20,20,25 | 5,5,5,5,5 |

| Steel | Temp., °F | Energy Absorbed, ft-lb WM | Energy Absorbed, ft-lb FL | Energy Absorbed, ft-lb 1 mm | Energy Absorbed, ft-lb 3 mm | Energy Absorbed, ft-lb 5 mm | Lateral Expansion, mils WM | Lateral Expansion, mils FL | Lateral Expansion, mils 1 mm | Lateral Expansion, mils 3 mm | Lateral Expansion, mils 5 mm | Shear-Fracture Appearance, % WM | Shear-Fracture Appearance, % FL | Shear-Fracture Appearance, % 1 mm | Shear-Fracture Appearance, % 3 mm | Shear-Fracture Appearance, % 5 mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 89,88,93 | 120,102,105 | 110,111,115 | 101,113,109 | 97,107,87 | 64,64,67 | 86,76,78 | 82,81,80 | 75,85,80 | 77,84,75 | 70,60,70 | 60,65,60 | 55,55,60 | 55,60,55 | 45,50,40 |
| | -40 | 52,46,56 | 61,73,94 | 81,71,77 | 74,99,94 | 91,82,51 | 41,38,46 | 48,54,70 | 54,57,40 | 59,75,71 | 70,54,45 | 45,40,45 | 40,45,50 | 35,40,45 | 35,45,50 | 35,30,20 |
| | -80 | 26,21,18 | 69,42,17 | 51,20,48 | 78,75,64 | 58,65,68 | 23,16,14 | 52,31,18 | 40,19,38 | 62,58,52 | 47,51,54 | 30,30,25 | 35,20,15 | 25,20,25 | 30,30,25 | 15,20,20 |
| | -120 | 14,10,16 | 17,9,20 | 11,10,13 | 9,31,36 | 11,7,12 | 12,7,12 | 11,8,14 | 9,8,11 | 6,20,24 | 5,5,10 | 10,10,15 | 10,5,10 | 0,5,10 | 5,10,40 | 5,5,5 |
| | 0 | 70,71,64 | 61,40,130 | 126,141,146 | 113,141,170 | 128,165,94 | 55,57,51 | 46,31,85 | 82,93,93 | 83,93,98 | 85,94,77 | 50,60,50 | 35,25,60 | 70,80,85 | 70,70,100 | 70,100,60 |
| | -40 | 34,64,53 | 21,36,17 | 165,101,130 | 138,110,98 | 107,115,112 | 28,49,41 | 18,29,17 | 96,76,91 | 91,82,74 | 79,83,81 | 40,50,45 | 20,25,10 | 100,60,70 | 60,45,50 | 50,60,60 |
| | 80 | 19,27,15 | 8,34,6 | 123,22,111 | 128,112,80 | 82,101,112 | 15,23,15 | 6,24,4 | 85,16,76 | 90,82,61 | 62,72,82 | 15,20,15 | 5,20 | 10,15,50 | 50,50,40 | 30,50,50 |
| | 120 | 10,8,12 | 13,9,7 | 6,14,23 | 23,51,65 | 22,72,67 | 8,8,10 | 9,6,5 | 3,16,20 | 16,36,49 | 16,55,51 | 5,5,5 | 5,5,5 | 5,5,10 | 10,20,20 | 10,25,20 |
| | 40 | 134,94,107 | 61,135,36 | 58,60,57 | 51,52,53 | 63,54,50 | 88,75,81 | 53,56,31 | 52,54,54 | 51,53,54 | 59,56,50 | 100,75,90 | 65,90,100 | 90,90,90 | 70,70,70 | 80,80,65 |
| | 0 | 100,88,66 | 56,40,35 | 50,41,36 | 37,33,36 | 44,36,36 | 74,69,51 | 50,37,36 | 48,40,37 | 35,33,37 | 44,35,35 | 80,70,60 | 50,40,65 | 40,60,40 | 30,30,30 | 60,40,40 |
| | 40 | 68,65,81 | 30,52,41 | 35,41,43 | 30,35,35 | 33,41,32 | 53,51,65 | 30,47,39 | 36,38,39 | 31,35,33 | 33,41,31 | 50,60,70 | 55,70,55 | 5,40,55 | 25,30,25 | 20,40,20 |
| | 80 | 23,40,23 | 36,27,31 | 20,25,15 | 15,20,18 | 6,17,9 | 20,34,20 | 31,22,27 | 16,20,14 | 12,15,14 | 4,13,7 | 25,35,25 | 30,25,30 | 0,20,15 | 5,5,5 | 5,5,5 |

APPENDIX G DPH Hardness of Butt-Welded Joints Investigated

| | Hardness, DPH | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | SAW 75 kJ/in. | | | SAW 180 kJ/in. | | | ESW | | |
| Steel | Base | Weld | HAZ 1 mm | HAZ 3 mm | Weld | HAZ 1 mm | HAZ 3 mm | Weld | HAZ 1 mm | HAZ 3 mm |
| 4 | 145 | 187 | 174 | 166 | 181 | 179 | 166 | 199 | 185 | 164 |
| 7 | 148 | 193 | 185 | 163 | 192 | 194 | 175 | 209 | 202 | 188 |
| 11 | 144 | 185 | 211 | 199 | 179 | 184 | 179 | 192 | 178 | 178 |
| 12 | 147 | 178 | 170 | 160 | 176 | 161 | 160 | 201 | 184 | 163 |
| 15 | 144 | 196 | 189 | 173 | 184 | 168 | 168 | 196 | 169 | 168 |
| 17 | 145 | 203 | 185 | 162 | 181 | 164 | 165 | 199 | 177 | 167 |
| 18 | 146 | 184 | 201 | 175 | 190 | 190 | 165 | 195 | 181 | 164 |
| 19 | 143 | 186 | 193 | 183 | 192 | 180 | 182 | 191 | 169 | 175 |
| L | 156 | 209 | 206 | 181 | 201 | 203 | 191 | 215 | 205 | 198 |
| N | 146 | 204 | 170 | 163 | 200 | 184 | 160 | 199 | 160 | 151 |
| U | 135 | 213 | 167 | 158 | 189 | 172 | 165 | 192 | 166 | 159 |

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